TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY
Julkaisu 630 • Publication 630

Jaana Hännikäinen

Electronic Intelligence Development for Wearable Applications

Tampere 2006

Tampereen teknillinen yliopisto. Julkaisu 630
Tampere University of Technology. Publication 630

Jaana Hännikäinen

Electronic Intelligence Development for Wearable Applications

Thesis for the degree of Doctor of Technology to be presented with due permission for public examination and criticism in Rakennustalo Building, Auditorium RG202, at Tampere University of Technology, on the 24th of November 2006, at 12 noon.

Tampereen teknillinen yliopisto - Tampere University of Technology
Tampere 2006

ISBN 952-15-1671-2 (printed)
ISBN 978-952-15-2015-0 (PDF)
ISSN 1459-2045

Jaana Hännikäinen

Electronic Intelligence Development for Wearable Applications

Abstract

In recent years there has been an enormous growth in the diversity and market penetration of small electronics appliances. Nowadays, people commonly carry such devices as mobile phones, Personal Digital Assistants (PDAs), and electronic sports accessories as an essential part of daily life. These devices are typically carried in pockets or bags and handheld when in use. User Interface (UI) devices are located on strategic parts of the body such as the wrist to facilitate free and easy access to them. An ease-of-use solution for carrying the increasing number of such personal devices is to embed or integrate them into clothing and accessories. Such solutions are known as wearable electronics systems and they are becoming essential aids for people in a wide range of applications areas such as communication, maintenance and repair, and location and navigation.

This trend has caused a growing need to create smaller and lighter devices which can be unobtrusively integrated and embedded in clothing. To achieve this, suitable applications for mobile environments as well as specific clothing-like technologies for their design and implementation need to be developed.

This study investigated specific applications utilising clothing as electronics platforms to ascertain whether usable clothing platform applications can be designed and implemented. This was done by implementing five wearable electronics application prototypes as clothing platforms: a fully functional smart clothing prototype for survival in arctic environments, two electrical heating prototypes to maintain users' thermal comfort conditions, a personal positioning vest for fishing, and a bioimpedance measurement suit for Total Body Water (TBW) estimation. For the implementation, application-specific solutions were utilized. Functionality, user acceptance, and usability of prototypes were verified. Usability evaluations were also made for a specific location and information service application. This was done to elicit the importance of usability evaluations in the wearable electronics field and also to evaluate user acceptance of the new technological devices and applications.

Specific materials required for the construction of comfortable clothing platform applications are Electrically Conductive Fiber (ECF) yarns, which are used in power and data transfer as well as in sensing elements. In addition, a concept of button component encasing for electronics components has been developed. Here, the components are hidden and connected to the clothes in a tailored way. Flexible Printed Wiring Board (PWB) is also utilized as a platform for a wearable antenna to achieve wearer comfort in wireless data transmission applications.

The implemented prototypes proved functional and it was demonstrated that such systems could be constructed utilizing clothing platforms. To ensure user acceptance, the usability of the systems and end user needs were considered key elements in the design process.

Preface

This study was carried out from 1998 to 2006 at the Institute of Electronics, Tampere University of Technology, Tampere, Finland.

I wish to thank my supervisor Prof. Jukka Vanhala for his support and encouragement during the work. First, I am grateful for the opportunity to work in the fascinating field of wearable electronics from the outset of this research at the Institute of Electronics.

The initiative for this research work was the former Reima-Tutta company, who gave me the opportunity to learn about applications combining electronics and clothing. I wish to thank the smart clothing research group for an inspiring working environment and for our valuable discussions during the course of the project.

I am also grateful to all members of our little textile team at the Institute of Electronics during these years. I have greatly enjoyed your company. I am also grateful to all my colleagues at the Institute of Electronics, especially the Personal Electronics group for providing such inspiring and innovative surroundings. Coffee breaks in the älkkäri were always stimulating moments in this research.

I would like to thank the reviewers of my Thesis, Prof. Tapio Takala and Dr. Juha Lehikoinen, for their constructive comments on the manuscript. Thanks are also due to Alan Thompson for revising the English of my thesis.

This thesis was financially supported by the Institute of Electronics, Graduate School in User-Centered Information Technology (UCIT), the National Agency of Finland (TEKES), The European Space Agency (ESA), Nokia Foundation, KAUTE Foundation, Foundation of Technology (TES), Finnish Konkordia Fund, EIS Foundation, and Jenny and Antti Wihuri Foundation. Their support is appreciatively acknowledged.

I would also like to thank my family and friends for their support and understanding during this process. Finally, thanks to you Marko for your love and encouragement during these years.

Tampere, November 1, 2006

Jaana Hännikäinen

Contents

List of Publications

This thesis consists of an introduction section and eleven publications [P1- P11]. The publications of this thesis are listed below [1].

[P1] Rantanen, J., Impiö, J., Karinsalo, T., Malmivaara, M., Reho, A., Tasanen, M., Vanhala, J., ”Smart Clothing Prototype for the Arctic Environment”, Personal and Ubiquitous Computing, Springer-Verlag, Vol. 6, No. 1, pp. 3-16, 2002.

[P2] Rantanen, J., Reho, A., Tasanen, M., Karinsalo, T., Vanhala, J., ”Monitoring of the User’s Vital Functions and Environment in Reima Smart Clothing Prototype”, Arai, E., Arai, T. & Takano, M. (Eds.), “Human Friendly Mechatronics”, Elsevier, Amsterdam, pp. 25-30, 2001.

[P3] Rantanen, J., Ryynänen, O., Kukkonen, K., Vuorela, T., Siili A., Vanhala, J., ”Electrically Heated Clothing”, Fifth World Multi-Conference on Systemics, Cybernetics and Informatics, IIS and IFSR, pp. 490-495, Orlando, FL, USA, July 22-25, 2001.

[P4] Rantanen, J., Vuorela, T., Kukkonen, K., Ryynänen, O., Siili, A., Vanhala, J., ”Improving Human Thermal Comfort with Smart Clothing”, IEEE Systems, Man, and Cybernetics Conference, pp. 795-800, Tucson, AZ, USA, October 7-10, 2001.

[P5] Rantanen, J., Alho, T., Kukkonen, K., Vuorela, T., Vanhala, J., ”Wearable Platform for Outdoor Positioning”, Fourth International Conference on Machine Automation (ICMA 2002), pp. 347-357, Tampere, Finland, September 11-13, 2002.

[P6] Hännikäinen, J., Vuorela, T., Vanhala, J., “Physiological Measurements in Smart Clothing: A Case Study of Total Body Water Estimation with Bioimpedance”, Transactions of the Institute of Measurement and Control, Hodder Arnold, 2006/2007, Accepted.

[P7] Rantanen, J., Jokinen, E., Reini, J., Vanhala, J., ”Usability Study of CityGuide: A Mobile Mapping Application”, Ninth IEEE International Conference on Telecommunication (ICT 2002), pp. 553-558, Beijing, China, June 23-26, 2002.

[P8] Rantanen, J., Hännikäinen, M., “Data Transfer for Smart Clothing: Requirements and Potential Solutions”, Tao, X. (Ed.), “Wearables and Photonics”, Woodhead Publishing, England, pp. 198-222, 2005.

[1] The surname of the author changed in January 2004. The maiden name, Rantanen, is used in publications before this date.

[P9] Hännikäinen, J., Järvinen, T., Vuorela, T., Vähäkuopus, K., Vanhala, J., “Conductive Fibres in Smart Clothing Applications”, Fifth International Conference on Machine Automation (ICMA 2004), pp. 227-232, Osaka, Japan, November 24-26, 2004. Accepted for publication as a book chapter in Mechatronics for Safety, Security and Dependability in a New Era, Elsevier.

[P10] Hännikäinen, J.; Mikkonen, J.; Vanhala, J., ”Button component encasing for wearable technology applications”, Ninth IEEE International Symposium on Wearable Computers (ISWC ’05), pp. 204-205, Osaka, Japan, October 18-21, 2006.

[P11] Salonen, P., Rantanen, J., “A Dual-Band Antenna on Flexible Substrate for Smart Clothing”, 27th Annual Conference of the IEEE Industrial Electronics Society, pp. 125-130, Denver, CO, USA, November 29-December 2, 2001.

Supplementary Publications

The following supplementary publications are not included into this thesis but they are closely related to its contents and therefore separated from the list of references.

[S1] Rantanen, J., Alfthan, N., Impiö, J., Karinsalo, T., Malmivaara, M., Matala, R., Mäkinen, M., Reho, A., Talvenmaa, P., Tasanen, M., Vanhala, J., ”Smart Clothing for the Arctic Environment”, Fourth IEEE International Symposium on Wearable Computers (ISWC ’00), pp. 15-23, Atlanta, GA, USA, October 16-17, 2000.

[S2] Kukkonen, K., Vuorela, T., Rantanen, J., Ryynänen, O., Siili, A., Vanhala, J., “The Design and Implementation of Electrically Heated Clothing”, Fifth IEEE International Symposium on Wearable Computers (ISWC ’01), pp. 180-181, Zürich, Switzerland, October 8-9, 2001.

[S3] Vuorela, T., Kukkonen, K., Rantanen J., Järvinen T., Vanhala J., ”Bioimpedance Measurement System for Smart Clothing”, Seventh IEEE International Symposium on Wearable Computers (ISWC ’03), pp. 98-107, New York, USA, October 21-23, 2003.

[S4] Vuorela, T., Hännikäinen, J., Vähäkuopus, K., Vanhala, J., “Textile Electrode Usage in a Bioimpedance Measurement”, International Scientific Conference on Intelligent Ambience and Well-Being (Ambience 05), 8 pages, Tampere, Finland, September 19-20, 2005.

[S5] Rantanen, J., Hännikäinen, M., Vanhala, J., **“**Wireless Communication Technologies for Smart Clothing”, Sixth Multiconference on Systemics, Cybernetics and Informatics, IIS and IFSR, pp. 259-264, Orlando, FL, USA, July 14-18, 2002.

[S6] Vuorela T., Kukkonen K., Rantanen J., Alho T., Järvinen T., Vanhala J., "RF Data Link for a Smart Clothing Application", Third International Workshop on Smart Appliances and Wearable Computing (IWSAWC 2003), pp. 7-12, Providence, RI, USA, May 19-22, 2003.

[S7] Salonen, P., Keskilammi, M., Rantanen, J, Sydänheimo, L., "A Novel Bluetooth Antenna on Flexible Substrate for Smart Clothing", IEEE Systems, Man, and Cybernetics Conference, pp. 689-794, Tucson, AZ, USA, October 7-10, 2001.

A Finnish patent has been granted for the invention presented in [P10].

[S8] Rantanen J., Mikkonen J., Järjestelmä galvaanisen yhteyden aikaansaamiseksi ja kappaleiden kiinnittämiseksi. Finnish patent number 115424. Granted 29.4.2005.

List of Abbreviations and Symbols

3D	three dimensional
AR	Augmented Reality
Avg	Average
BWC	Body-Wearable Computer
C	Heat loss by convection from the surface of the clothing
CD	Contextual Design
CPU	Central Processing Unit
ECF	Electrically Conductive Fiber
ECG	ElectroCardioGram
E_d	Heat loss by water vapor diffusion through the skin
EDGE	Enhanced Data rates for GSM Evolution
EMI	ElectroMagnetic Interference
E_{re}	Latent respiration heat loss
ESD	Electrical Static Discharge
E_{sw}	Heat loss by evaporation of sweat from the skin
e-textile	electronic textile
FAN	Fabric Area Network
GPRS	General Packet Radio System
GPS	Global Positioning System
GSM	Global System for Mobile communication
H	Internal heat production in the human body
HCI	Human Computer Interaction
HMD	Head-Mounted Display
IET	Interactive Electronic Textile
ISM	Industrial, Scientific, Medical
K	Heat transfer from the skin through the clothing
k	constant
L	Dry respiration heat loss
LCD	Liquid Crystal Display
LED	Light Emitting Diode
Li-ion	Lithium-ion
Li-polymer	Lithium-polymer
mA	milliampere
MD	Mini Disc

MHz	megahertz
MIT	Massachusetts Institute of Technology
mm	millimeter
MP3	Moving Picture Experts Group 1 layer 3 audio encoding
N	newton
NiMH	Nickel Metal Hydride
°C	Degrees of Celsius
PAN	Personal Area Network
PDA	Personal Digital Assistant
PPM	Personal Position Manager
PWB	Printed Wiring Board
PWB	Printed Wiring Board
R	Heat loss by radiation from the surface of the clothing
RF	Radio Frequency
RFID	Radio Frequency IDentification
R_P	Parallel resistance in human body
Sd	Standard deviation
SMS	Short Message Service
TBW	Total Body Water
TESC	Technologies Enabling Smart Clothing
UI	User Interface
UMTS	Universal Mobile Telecommunications System
V	voltage
VRD	Virtual Retinal Display
WLAN	Wireless Local Area Network
Ω	ohm

1 Introduction

In the early 1990s Mark Weiser described the future of computing as disappearing from the consciousness of people [218]. This means that computer systems will be unobtrusive and so easy to use that people can forget them and work with them without actively thinking of them. This so-called ubiquitous computing approach also implies the invisibility of hardware devices and continuous connectivity to information networks. Size reduction of electronics systems enables their integration into everyday objects and, at the same time, the distribution of computing capabilities to the surrounding environments [218, 219].

To realize this computing approach in practice, further development is needed such as in the miniaturization of electronics as well as in new types of specialized User Interfaces (UIs) for ubiquitous applications. Hardware technologies having the strongest influence are the numerous emergent wireless communication technologies, improving processing and storage capacity of embedded platforms, new electronics packaging technologies, as well as high-quality display technologies [207].

Today, the latest technological development has already made it possible to construct small and light electronic appliances, which can be carried on the person almost anytime and anywhere. Typical examples of these are mobile phones and Personal Digital Assistants (PDAs), which enable continuous connections to information sources as well as time and location dependent calendar and memo services. In other words, such devices make offices as mobile as their users. Heart rate monitors for fitness applications and Global Positioning System (GPS) devices represent another group of electronics appliances mostly utilized for leisure activities. People are becoming accustomed to carrying different assisting electronics appliances such as mobile phones and MP3 players, regardless of time, location, and social situation. All this indicates that the market is well-prepared to accept new technological equipment [207]. A natural ease-of-use solution to permanently carrying these devices on the person (or their functionality, to be exact) is to embed them in clothes or clothing accessories [42, 120]. These kinds of devices are known generally as wearable electronics appliances.

Since the user is in close contact with wearable electronics, it is obvious that users' acceptance is of fundamental importance. Some of the attributes affecting this are usefulness, easy and safe usage of the systems, social acceptance, and wearability. A crucial issue is how the electronics are sited and attached to soft clothing material. This integration of electronics has a direct bearing on the usage comfort of clothing.

To speed up the emergence of wearable electronics, new application concepts are needed as well as piloting practical prototypes and user tests. First, it is necessary to pilot wearable electronics prototypes and applications that represent realistic possibilities as personalized mobile platforms and which also fulfill the wearability requirements. These can be implemented by applying available technologies in new application-specific ways to target applications. Second, there is a need to develop new unobtrusive technologies that are suitable for use in mobile environments.

1.1 Scope and Objectives of the Thesis

This thesis presents new wearable electronics applications and hardware technologies needed in the application design and implementation. Specifically, this thesis deals with applications integrated into clothing. In this context the term *wearable electronics* refers to electronics systems that are worn during use. S*mart clothing* refers to clothing applications that contain electronics and non-electronic features enhancing and augmenting the functionality of ordinary clothing [P1, P2]. In this latter case, the emphasis is on clothing as an implementation platform for electronics placements.

The main research question of this thesis is whether the clothing can be used as a platform for electronics. This address to the following problems: what kinds of technologies and materials are suitable for the clothing and how usable and comfortable wearable applications can be constructed? These problems are studied in this thesis with the help of research prototypes. Figure 1 presents the structure and the contents of the publications of this thesis. The contents are divided into two main parts: full-scale wearable electronics application prototypes, and the evaluation and development of enabling technologies for smart clothing. The publications of this thesis present five wearable electronics prototypes and evaluate their functionality and usefulness. Key enabling technologies for smart clothing construction are the communication between different parts of smart clothing and the implementation of physical electronics connections inside the clothing.

The starting point for this research was a full-scale smart clothing prototype for the arctic environment called *Cyberia* (1998-2000) [P1, P2]. The aim of this prototype design and implementation was to study the possibilities for utilizing information technology, electronics, and advanced fiber and textile materials to produce better functioning clothes. Hence the research also considered the overall concept of smart clothing and its elements, i.e., electronic and non-electronic functions as well as functional textile materials. Cyberia represents a special-purpose application targeting accident prevention and automated help calling in accidents.

At that time the prototype embodied a different approach to wearable electronics implementation compared to other applications in the field. These latter applications were usually full-scale wearable computers equipped with visible parts such as head-worn displays [13, 143, 190, 197] or single functioning accessories or textile-based solutions such as sensors embedded inside shoes or textile keyboards [144, 147]. The aim in the Cyberia project was to design and implement a full-scale application prototype having the appearance of ordinary clothing. However, during the Cyberia project several challenges were encountered in wearable electronics construction. These involved the need to develop suitable clothing-like materials, robust enough for clothing platforms, the need for miniaturization of electronics, and the development of washable electronics and placements. Other important issues to be addressed were the usability of the system and also cost. In the later prototypes the aim was to discover solutions to overcome these challenges, the focus being on clothing-like materials, washability, and usability.

The Technologies Enabling Smart Clothing (TESC) project which succeeded the Cyberia project set out to study in greater detail a number of technologies and their suitability as clothing platforms (2000-2003). The goal in the first year was to examine the basic functionality of smart clothing. Research was conducted into additional heating possibilities in clothes and their accessories. The objective here was to design and implement an electrical heating prototype, which would provide an additional heating option for its user [P3, P4]. This research prototype made it possible to investigate electrical heating implementation in clothing and also how users would react to this smart clothing application.

In the second year the TESC project focused on personal positioning, which is an essential part in ubiquitous and wearable applications, being dependent on the situation and the physical surroundings. The goal here was not actually to develop a new positioning method, but rather to evaluate the usefulness of a smart clothing positioning prototype and to design an ease-of-use application. As a result, the main topics of research were component distribution in clothing, users' acceptance of the application, and electronics integration. Fishing was selected as the target application and a fishing vest was chosen for the smart clothing platform [P5].

In the third year of the TESC project the focus was on physiological measurement implementation in a clothing platform. The target application selected was a bioimpedance measurement system. The aim was to examine the applicability of the system to water balance estimation while also taking into account user comfort [P6]. Since clothing is in close contact with the skin, it is assumed to provide an ideal platform for personal and continuous physiological measurements. Commercial gel-paste electrodes were found to be unsuitable for mobile measurements and thus special emphasis was placed on the reliability of comfortable textile-based sensing elements.

Usability and user comfort play key roles in applications where users are mobile and the usage environment is continually changing. The aim of the CityGuide application for mobile phones or PDAs was to study user acceptance and the usability of the wearable electronics information system [P7].

Designing smart clothing is a challenging process since it involves the integration of hard electronics with soft elements. Attention needs to be paid to the particular properties of the clothing and also how these can be retained in smart clothing applications. The soft and dynamic nature of clothing requires flexibility from the additional components that are integrated into it. Therefore, technologies that can improve the smart clothing performance from the user point of view are also studied in addition to functionality. These technologies include the suitable data transfer methods for the clothing environment and the usage of connection mechanisms suitable for the clothing structure [P8 - P11].

Electrically Conductive Fibers (ECFs) are considered to be good solutions in clothing because they are light and more flexible than conventional materials such as plastic insulated cables or metal electrodes. It is an important first step to determine whether it is possible to utilize ECFs in data and power transfer and in sensing element implementation [P1, P2, P4, P6, P8, P9]. The new technologies to be implemented in a new platform typically pose a number of challenges. One of these was found to be the reliability of ECF materials in connections. Consequently, it was necessary to ascertain whether these ECF materials could be utilized to form reliable contacts with hard electronics [P8, P9]. In addition, the connections between different pieces of clothing or between the electronics and clothing appear to need clothing-like solutions. One such novel solution might be the use buttons as covers for the electronics which could be sewn onto the clothing by using ECF [P10]. The aim was to examine the functionality of this concept.

In addition to ECFs, flexible Printed Wiring Boards (PWBs) are thought to be better solutions for clothing than conventional rigid PWBs. As a result the suitability of flexible PWBs for wireless data transfer antennas and clothing applications are investigated [P11]. In this study there are actually two different research approaches. The first examines the suitability of flexible material for antennas and the second considers the suitability of flexible antennas for use in clothing application in close proximity to the human body.

1.2 Outline of the Thesis

This thesis contains eleven publications and an introduction. The publications embody the main results of the thesis which comprise prototype implementation and evaluation as well as an examination of data transfer techniques and connection mechanisms.

The introduction presents various publication findings and describes the application field. Chapter 2 starts with definitions of concepts utilized in the wearable electronics field, with the emphasis on smart clothing and its relation to other concepts utilized. Next, there is a survey of wearable electronics applications which introduces some potential uses of wearable systems. Chapter 3 deals mainly with the smart clothing design process and also discusses the general requirements of smart clothing design. Additionally, factors related to user acceptance of the systems are explained. The smart clothing concept model introduces a method for placement of the electronic components

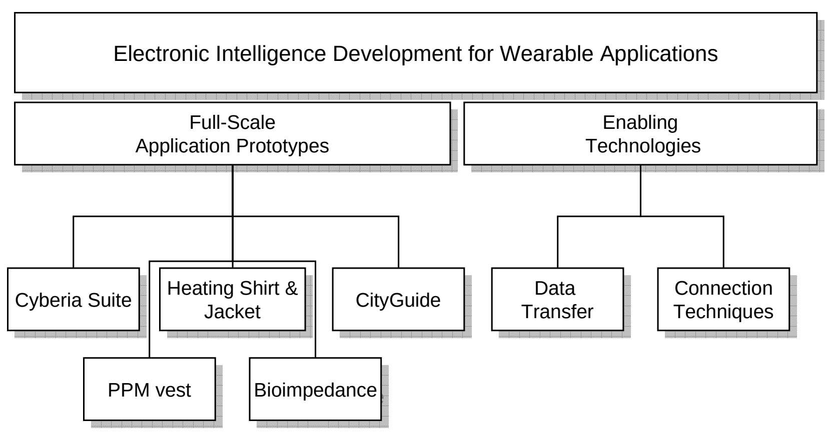

Figure 1. Structure of this Thesis.

in the design between different clothing layers. The electronics architecture for smart clothing applications is also introduced. Chapter 4 presents the major results of the research. First, the designed and evaluated smart clothing prototypes are described and the findings of these evaluations are discussed. Second, technological outcomes are explained, particularly those relating to data transfer utilizing ECF, connections utilizing ECF, and ECF usage in electrode materials. Chapter 5 contains a brief summary of the publications included in this thesis and provides an explanation of the Author's contribution. Finally, Chapter 6 presents the main research conclusions of the study.

2 Wearable Electronics

Wearable electronics is still a fairly new field of research and as a result much of the terminology has still to gain widespread acceptance. The history of wearable electronics goes back to 1960s when Edward Thorp and Claude Shannon designed, implemented, and tested the first known wearable computer intended for roulette number prediction [200]. The system, the size of a cigarette pack, consisted of a twelve-transistor Central Processing Unit (CPU), two microswitches as an input device for the toes, a loudspeaker as an output device, and a radio link. This application represents a special purpose system capable of doing only advanced specified tasks and also demonstrates the important feature of smart clothing applications, i.e., the usage of special UI devices. Its use, however, was forbidden in casinos at the time. One of the first public uses and, therefore, a starting point in the development of wearable electronics was Sutherland's implementation of the Head-Mounted Display (HMD), which was utilized in virtual reality applications [84].

In terms of general awareness, wearable computers have emerged as general-purpose computer systems that are as mobile as their users, moving with them anytime and anywhere. At Massachusetts Institute of Technology (MIT), in particular, a group of university students and staff started to wear their computers continuously in the 1990s [120, 183, 185]. The first worldwide conference on wearable computers was held in 1997 [77]. Since then the manifestation of wearable electronics has covered systems from full-scale wearable computers to small-scale, special-purpose applications to be worn only during usage. In the future, personalized mobile platforms can provide high-performance computing for a variety of user applications, and an interface for controlling the surrounding environment. Apart from smart phones, very few people carry a full-scale computer with them all the time [115, 183].

2.1 Wearable Electronics Field

The range of electronics systems that are worn or carried during usage is diverse. The main concepts related to wearable electronics are illustrated in Figure 2, which sets out the relationships between the concepts and the way they are employed in the present thesis.

Wearable electronics is regarded as a general term for the systems or appliances that contain electronics and that are carried or worn during usage. *Wearable technology,* on the other hand, does not define the type of technology utilized, i.e., electronics are not necessarily needed. Therefore, applications are divided into wearable electronics applications and clothing platform applications. The latter include textile and fiber technology, although these systems usually also contain computing capabilities, sensors, and UIs typically represented by small portable electronics, gadgets [204]. In addition, wearable technology systems are useful only while worn.

Wearable computers are defined as computer systems that are carried at least during operation and utilized with only one hand or hands free [11]. Typically, an ordinary desktop computer has been shrunk to a smaller package and UI devices have been changed into devices that are suitable for mobile use. The usage of these systems can be categorized into two groups. The first comprises smaller scale wearable computers intended for special applications such as maintenance assistants or heart rate monitoring equipment. The second group is larger scale systems intended for general personal help in everyday situations. These fully functional personal computers are worn in belts, bags, or clothes and equipped with typical computer accessories, i.e., pointing and feeding devices and displays for feedback. Mizell describes these two approaches by means of a tool model and a clothing model [135]. The former refers to special purpose wearable applications intended to be worn only during the specified operation whereas the latter refers to the wearing of the computer throughout the day like an article of clothing. Wearable computers are regarded as a special case in wearable electronics systems.

According to the narrower definition of wearable computers, these general-purpose systems are seamless parts of a user's personal space being constant in operations and interactions, unmonopolizing and unrestrictive for the user, and providing the means to sense, react, and communicate with the environment while also protecting its user's privacy and independence [117, 118, 121]. This latter definition defines the usage of the system as akin to the usage of clothing. These wearable computers are, therefore, also known as underwearables, which emphasizes their integration into users' personal spaces in clothing [116]. Wearable computers are also known as Body-Wearable Computers (BWCs) indicating that they are carried close to the user's body [37]. Weiser suggested that in the ubiquitous era computing will also be embedded in clothing [219]. Therefore, wearable electronics in this thesis is concerned as a part of ubiquitous computing, being a way to access distributed services. In the literature these computing approaches can also be distinguished from each other. In their purest forms, ubiquitous computing is distributed to the surroundings and sensing and processing of wearable computing is performed by the user without help from the surroundings [166].

To highlight wearability and the clothing usage of wearable computing systems we adopted the term smart clothing to refer to special-purpose wearable computers or electronics integrated in clothing. Smart clothing is composed of ordinary clothing with added intelligent structures. These structures can be formed with electronics, non-electronic equipment, intelligent textile materials, or their combinations [P1, P2, S1]. The purpose of smart clothing is to improve or augment the functionality of ordinary clothing in various ways such as providing better protection for their users or providing new ways to utilize their clothing [P1, P2, S1]. In order to complete our definition of smart clothing we also require the systems to include facilities to sense their user or the environment and the capability to react to these measurements [153, 154, 165, 203]. Such reactions can be autonomous actions as with the control of electrical heating by human temperature measurements [P3, P4, S2] or provision of information to users [P1, P2, S1]. Smart or *intelligent clothes* are as intelligent as their designers.

Mann's definition of smart clothing is based on mobile multimedia, wireless communication, and wearable computing; such attributes, however, are not necessarily required in the definition of smart clothing adopted in this thesis [114, 119]. Instead we emphasize the specificity of applications as opposed to general-purpose wearable computers [P2]. Underwearables are, in fact, smart clothes according to our definition. However, the term might imply that the clothing platform is actually underwear in the popular sense, and this is why it is not used here as a synonym for smart clothing.

Smart and intelligent may be somewhat misleading terms for defining these applications. However, these prefixes are adopted in the present study because they are widely used by the wearable computer research community and by the general public. Another term utilized for smart clothing is *computational clothing,* which highlights the integration of computing capabilities into clothing such as storage, processing, retrieval, and transmission of information utilizing clothing-based systems [9]. *Interactive Electronic Textiles* (IETs) or *electronic textiles* (e-textiles) are conventional concepts for clothing platform usage for electronics systems [40, 122, 131].

Intelligent or smart textile materials themselves include sensing elements, actuators, or context-sensitive and adaptive electronics structures [203]. Smart materials can be divided into three categories, namely *passive smart textiles*, *active smart textiles*, and *very smart textiles* [195]. Passive smart textiles can only sense their surroundings, whereas active smart textiles also include actuation, i.e., they can respond autonomously to the measured surroundings or stimuli. Very smart textiles, too, can adapt their behavior according to different situations. *Functional* and *technical textile* materials are often regarded as being smart materials. However, they do not fulfill the definition of smart materials. Functional and technical textile materials are textiles that are, for example, breathable or fire-resistant, i.e., they meet high technical and quality requirements and give functionality to the fabric [68].

As a consequence of the integration of wearable electronics or computing into clothing platforms, potentially with intelligent textile materials and non-electronic equipment, the outcome is smart clothes. Non-electronic equipment may, for example, be a fire kit,

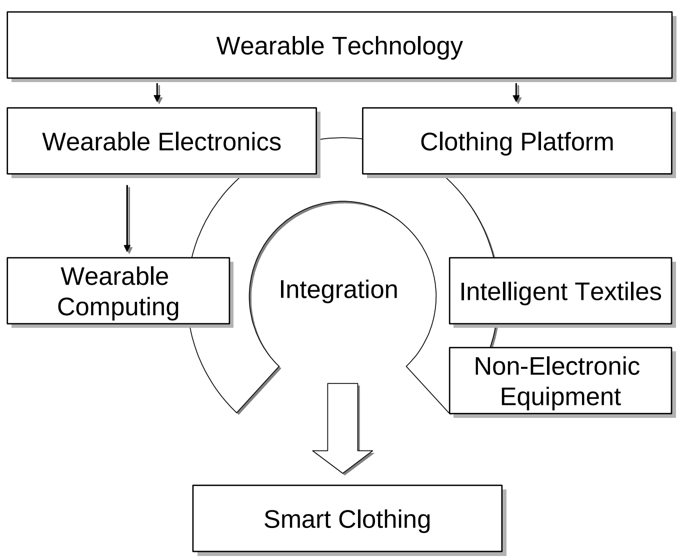

Figure 2. Concepts in the field of wearable electronics.

which is covered and protected from getting wet. The crucial point is that such equipment is necessary in the application in question. The clothing platform includes clothes and their accessories manufactured from conventional and functional textile materials.

2.2 Wearable electronics applications

Wearable electronics applications can help people to survive in their every day life or workplaces by providing assistance or the tools for coping with a range of tasks. Numerous commercial products are available as technologies and dedicated devices. However, there are only a few examples of integrated smart clothing applications. By contrast, there is a multitude of wearable electronics applications including much mobile computing equipment, portable music players, heart rate monitors, wrist-worn computers, and pedometers, all of which can be utilized while on the move. These applications are typically used for hobbies and entertainment purposes.

The first reported commercial smart clothing applications were jackets that contained a MP3 player and a mobile phone [56]. Later came clothes for snowboarding [161, 211]. The snowboard jacket contains an integrated fabric UI and Mini Disc (MD) player or a MP3 player. A wearable electrical heating jacket designed for mountaineers and a rescue vest containing an integrated communication system have also been introduced [212, 213].

Examples of accessory-based applications are running shoes with intelligent cushioning and running shoes connected to a music player to support and guide the running performance with the aid of music [215, 216]. In addition, a jacket containing pockets for a variety of electronics equipment has been launched [71]. This jacket also provides the option of utilizing a solar cell panel for battery charging and a patented Personal Area Network (PAN) solution for device connections. Symbol Technologies has developed a commercial data collection system for applications in industry such as warehouse inventory and transportation control. This is designed to be worn on the wrist and equipped with a finger-worn bar code reader for ease of data collection [188].

2.2.1 Assisting Applications for Disabled

Several wearable applications for individuals suffering from physical, cognitive, or sensory impairment have been reported, from handheld applications (e.g. eye glasses) to prosthesis [167]. Typical examples are guidance applications for the visually impaired such as VibraVest, which provides tactile user feedback about nearby objects [116]. Another example is a haptic navigation guidance vest, which contains four by four arrays of tactile micromotors in the back of the vest to provide haptic directional information [41]. Tactile feedback can also be utilized to assist the deaf [20].

In addition to a tactile feedback interface, tone and speech interfaces have also been evaluated for orientation aid interfaces for the visually impaired [167]. Additional context information, together with the traditional cane, a guide dog, and environmental sounds have been shown to complement visually impaired navigation by enabling the proximity detection of people, animals, and objects [163]. The user is warned by haptic feedback and, therefore, avoid unwanted contacts or speaking to persons out of the hearing range. The Drishti application guides the visually impaired or disabled to desired locations using speech UI and GPS [64]. The system notifies context and user preferences while recommending the route to be taken. These applications are entirely wearable and need no fixed infrastructure in the environment.

Radio Frequency Identification (RFID) technique is also utilized for visually impaired navigation and way finding [225]. RFID tags are utilized to form tag grids. Location coordinates and surrounding information is preprogrammed onto tags which can then be read by the user with the aid of a reader.

The above applications are all designed to help the disabled directly. However there are occasions in which assistance is needed to enable others to communicate with the disabled. An example of this is a wearable American Sign Language recognizer, which converts its wearer's sign language into spoken words utilizing a cap-mounted camera to track hand gestures [187]. Another approach is to utilize gloves, in addition to a camera, to provide information in cases when the hands obscure each other from camera view [31].

2.2.2 Assisting Applications for Guiding, Navigation, and Information Access

Examples of wearable applications are the range of guiding, navigation, and information applications, which can help people in unfamiliar surroundings reach their desired destinations or provide information about shops, tourist attractions etc. For implementation of these applications, various positioning techniques are needed. For outdoor positioning, GPS is typically utilized.

The Touring Machine is a bulky backpack-wearable computer system combining mobile computing and augmented reality (AR) in a guiding application at a university campus area [44]. Similar AR systems are also utilized for larger geographical areas [197]. There is also a wearable guide designed for use on a campus area and capable of representing location-based multimedia information [76].

Metronaut, also for use on a university campus, is another wearable computer prototype for scheduling and guiding tasks. The system includes a reader for scanning barcodes, which mark important locations in the area. While moving around the campus, a user can scan the barcode and the system guides the user to the next meeting place [178].

Other context-dependent information may also be added to these applications. One such example is a city touring guide that only gives information relevant to the user's geographical location, ignoring information too far from that location (i.e. out of the virtual information visibility range) [101]. A smart sight tourist information system goes even further, providing help in overcoming language barriers in foreign places as well as navigation assistance and aid in storing and organizing memories [227].

All the application examples of integrating GPS-based guidance systems in wearable computers utilize backpacks and also usually bulky HMDs to enable visibility of real world- and computer generated-assistance in the same visual field. Because of the inconvenience of these large and bulky GPS applications, we have also studied integrating GPS in clothing in inconspicuous ways [P5]. This application was designed for fishing and thus, required small and lightweight electronics.

2.2.3 Assisting Collaborative and Context-Aware Applications

Wearable electronics have been proposed as help in remote communication and establishing a collaborative community to enable conversation while performing other tasks [17]. These collaboration tasks are particularly well-suited for maintenance, repair, inspection, and construction tasks, in which expert advice can be needed. An example of such an application is the maintenance and repair of trains needed by railroad technicians. In this application, expertise at a distant location can provide help in fault diagnosis and repair, utilizing digital data, audio, and images [173].

A step forward is the collaborative wearable systems that can also sense the environment remotely [13]. This makes communication between the parties more natural because context-related information can be sensed in both places with no unintentional filtering. Wearable applications can also assist people with no network connections and help, for example, in the acquisition of new skills for carrying out complex tasks [142]. These, however, are not collaborative applications.

Context-aware or situation-aware computing utilizes context information, i.e., the location, environment characteristics, and the user’s condition or activity in order to provide relevant information or services to the user [34, 174]. One of the most important features in mobile and wearable electronics is to provide continuous access to information sources and thereby provide help in a variety of daily routines [11]. However, for wearable computing applications, in particular, relevant information sources or information representation and ease of access is dependent on a number of factors. These include the identities of the individuals involved, the location and activity of the user, and the time as well as informative and easy to use UIs [35, 191]. Typically, this context sensing is based on defining the user’s location [1, 81]. A simple example of a context sensing smart clothing application is a necktie accessory, which can sense the aural information near the user and recognize speaking, noise, and silence as well as the status of the user’s movements [171].

A well-known application to improve overall quality of life is Steve Mann’s WearComp system [118]. His system was inspired by still-life imaging and contains a camera-equipped wearable computer to allow users to observe their surroundings. This can also enhance their security, for example, by alerting the user of potential danger [114, 118].

Remembrance agent is an example of an application that augments the user’s memory [165]. The system relies on context information and suggests relevant documents appropriate to the current situation. It, therefore, acts as an extension of the users’ memory.

2.2.4 Assisting Applications in the Workplace

Wearable electronics can also provide important benefits for people in a wide range of jobs. These include assistance in mobile office environments as well as in dangerous environments such as the military, the rescue services, or in space. However, most applications reported relate to manufacturing, maintenance, and inspection tasks such as aircraft maintenance, repair, and inspection [143, 172]. A wearable computer can provide additional information in diagnosis, troubleshooting, and repair as well as aid to memory for inspection lists, in which certain steps must be taken to ensure safety. In addition, significant savings in time can be achieved when information is available through wearable systems [180]. Wearable computers are also utilized to assure quality in food processing plants and to help in the documentation used by bridge inspectors by means of speech input assistance and the addition of automated notices to collected data [136, 190]. A wearable computer utilized with HMDs can provide vital information without interrupting the progress of the job by also enabling access to the relevant expertise [45, 199].

Wearable computers have also been proposed for weapons maintenance as well as for training tasks for military personnel [12, 21]. Wearable applications in the field are challenging to design because of the unpredictable nature of the military context. Additional equipment should not encumber the user and hands free operation is clearly desirable. Fortunately, military clothing and other equipment offer considerable space for incorporating components. An HMD, a speech input, a navigation system, and a weapon system offer significant advantages such as hands free operation, information retrieval in the field, location information, and help in the preparation of field reports [27, 230].

A clothing-like approach has been taken in the development of Sensate Liner, which detects bullet wounds in the torso using optical fibers [102]. The system is constructed in a shirt. In addition to penetration occurrence, classification and localization, it can measure heart and respiration rates and also movement. This system demonstrates techniques which are also generally needed in wearable medical monitoring.

Firefighters can also experience similar life-threatening environments involving threats from radiation, high temperatures, and air shortages in air bottles. For stricter supervision in such working conditions and better communication between individual firefighters and the leader of the team, smart clothing systems should be able to withstand high temperatures [59, 94]. Wearable computers are also recommended for helping rescuers in disaster zones to provide assistance in such areas as data collection tasks and locating rescue team members [92].

Though manned space travel has a history of several decades, a microgravity environment leads to changes in physiological conditions with long-term missions being particularly risky [7]. Important health issues in space concern radiation, loss of bone mineral density, behavioral changes caused by isolation, and changes in cardiovascular and pulmonary systems. In order to counter these risks to health, spacecraft and space stations are equipped with appropriate data measurement and collection devices. Space travel provides an ideal opportunity to utilize wearable systems to ensure long-term health monitoring before, during, and after journeys. An example of this is a sensor jacket, which can record ElectroCardioGram (ECG), pulse, and tremor and also as well as produce muscular and cardiovascular loads with a hand dynamometer [50]. Help in dangerous extra-vehicular or difficult tasks is also provided by wearable computers [23, 38, 155].

2.2.5 Assisting Wellness Technology Applications

Physiological measurements in different forms are considered to be the key applications of wearable systems. Clothing is in close contact with the skin, providing the chance to perform measurements which require skin contact. Clothes also offer privacy in personal health monitoring. Perhaps the most popularly known wearable electronics health monitoring systems are the heart rate monitors that are widely utilized in sports [69]. These systems are usually based on a plastic-based sensor belt worn around the chest and a UI on the wrist. More clothing-like properties for wearable electronics systems are achieved by utilizing ECF-based sensing elements. These are being studied in several research institutes and ECF electrodes are typically utilized to measure ECG, heart rate, and skin conductivity [P2, P4, 145].

The earliest reported systems for physiological signal monitoring were usually simple and single- or two parameter-devices measuring, e.g., ECG, temperature, or accelerations of individuals [32, 62, 189]. Later, prototypes for measuring typically skin temperature, heart rate, ECG, and accelerations were implemented [58, 107, 208]. Nowadays the area of wellness technology has received considerable publicity for a number of reasons such as population aging and an increasing number of different life-style related diseases. Present physiological monitoring systems are typically based on wrist-worn devices or clothing-based systems [5, 6, 36, 87, 107, 208]. Various shirt, vest, suit, and accessory solutions contain textile electrodes to measure several physiological quantities and accelerations of individuals [96, 149, 209]. In addition to data collection, wearable systems can be utilized for real-time feedback to enable continuous monitoring in every day life, thereby improving non-institutional care [126].

Other wellness technology applications include systems for rehabilitation purposes to enable automated data collection and transmission to rehabilitation supervisors such as trainers and doctors, as well as feedback to rehabilitants [53]. An experimental system to estimate when and what type of food a person is eating has also been reported [2]. Prototypes to measure physiological quantities for emotional state evaluations have also been designed [5, 6, 63]. Wearable monitoring systems for measuring data on the user and the environment to evaluate a user’s state of alertness are important aids in promoting worker safety in dangerous conditions. These systems are implemented, e.g., for motor sports and industrial applications [82, 83].

2.2.6 Entertainment and Leisure Time Applications

Various popular wearable electronics systems have been designed and implemented for musical entertainment. In addition to these, systems to help in creating networked music have also been designed and implemented [112, 140, 193]. Items of clothing such as jackets, pants, or gloves become musical instruments when equipped with the necessary electronics and tactile sensors to create music and a network connection for shared listening and musical performance. A wearable system for creating every-day music based on different sensors in the user’s jacket produces music based on the user’s movements and environment [128]. Computer augmented art is also created utilizing apparel such as footwear [146, 147]. With this system, a dancer wears special shoes equipped with sensors to measure different kinds of steps. According to the steps, the system generates music and computer graphics.

Music has also been utilized as a motivator in sport performance, e.g., to guide and support exercise with suitable music styles and tempos [224]. Another example of wearable electronics usage in sport is a form of training help for professional skiers [132]. The system contains sensors to measure the athlete’s movements, foot pressure, ski rotation, and speed. Together with video and sensor data, trainers and skiers can identify skiers' strengths and weaknesses. Reima Smart Shout is an example of communication equipment intended specifically for snowboarders [134]. The main purpose of the system is to provide an easy-to-use UI to enable ease of communication with a snowboarding group. Another group communication application for ski instructors has also been investigated [217]. This system informs the user if other group members are nearby.

AR-based wearable electronics have been utilized for different games. Typical examples are games that have been changed from desktops to mobile environments in order to form a combination of computer-generated and real worlds [3, 26, 196]. HMDs or PDAs are typically utilized as feedback devices. However, games for carrying fewer devices such as smart phones have also been designed [25]. Another type of AR applications is a training help for billiards which assists the player in executing strategic shots [79].

3 Smart Clothing Design

Smart clothing aims to provide greater added value to its user than either traditional clothing or separate electronics devices. In practice, this means that smart clothing systems usage must offer more benefits than drawbacks to achieve user acceptance [137]. Therefore, it is evident that the smart clothing design process is based on users and their needs. This is also a way of ensuring that smart clothing prototypes are designed for real needs rather than invented ones. The overall design of wearable electronics systems utilizing a clothing platform or accessories is a demanding process since it requires multidisciplinary group work. In addition to electronics and software engineers, representatives from human sciences, clothing and textile sciences, material science, and industrial design are needed to ensure functional designs [P1, S1].

3.1 Smart Clothing Design Flow

A smart clothing design flow is presented in Figure 3. This design flow results from the experiences of implementing wearable electronics prototypes for this thesis. The starting point for the design is obviously the decision or assignment that something needs to be done. On the basis of the assignment, appropriate team members can be assembled so that the necessary expertise is represented in the working group. The working group can then make the preliminary problem statement and define the target user group for the application. Since smart clothing applications are usually intended for specific applications, the user group must also be specified. This is necessary during the next phases, which focus in more detail on the functionality and requirements of the system.

The team members can now start gathering data on user needs and performing a literature background survey, if necessary. These two phases can be carried out simultaneously along with other information gathering such as target group interviews or questionnaires. The findings are collected and shared at a group meeting to allow the team to evaluate the assignment in terms of any drawbacks such as risks or problems in the application area. It is also necessary to set goals for the project at this stage, to ensure that all the team members share a common aim. Experience in these previous phases will also provide the members of the team with a shared understanding of the background to the project. This helps in the design phase, most of which can be done separately. During this goal definition phase the general requirements for the application are also set. These may include the limitation of extra weight in the clothing or involve matters concerning the operating lifetime of the system with one battery charge. The requirements set in this phase guide the execution of the sub-designs.

At the next stage the design of the smart clothing application can be split into sub-design projects. These typically include areas such as user comfort and usability design; information technology design involving electronics, software, and telecommunications; textile and clothing design; and industrial design. The various parties make their own design decisions and are responsible for the functionality testing. Since the separate projects all form parts of a bigger project, regular meetings are necessary to update all members on a range of issues such as the project schedule, problems and challenges arising during the design, and the compatibility of subcomponents. In addition, clear interfaces need to be established between the parties working in shared projects such as between an encasing designer and an electronics designer.

After making parallel designs, the team can also meet to collaborate on some functionality testing to double-check that the system is ready for the integration. If this functionality testing fails, problematic parts will be redesigned. Preliminary usability or user comfort testing can also be done to ensure proper integration to clothing. In addition, throughout the design process there is continuous evaluation of the usability of UI devices whenever something new is introduced. After these evaluations, the system is ready for the integration. Clothing specialists are normally responsible for this final integration into clothing.

After integration, the prototype should first be tested under laboratory conditions and also in authentic usage environments to ensure basic functionality. If the functionality tests show the system to be mostly functional, usability tests can be conducted to evaluate UIs and the overall wearing comfort of the system. Failures are often due to compatibility problems between different sub-designs. Such problems need to be solved before the usability evaluations. After testing, it is possible to determine whether the system fulfils the set requirements. If it does not, it will be necessary to make repairs to the sub-designs. In this loop the design process can proceed, provided the goals are achieved. Finally, the first prototype is implemented.

After After these tests, the results will need to be analyzed, particularly when it is

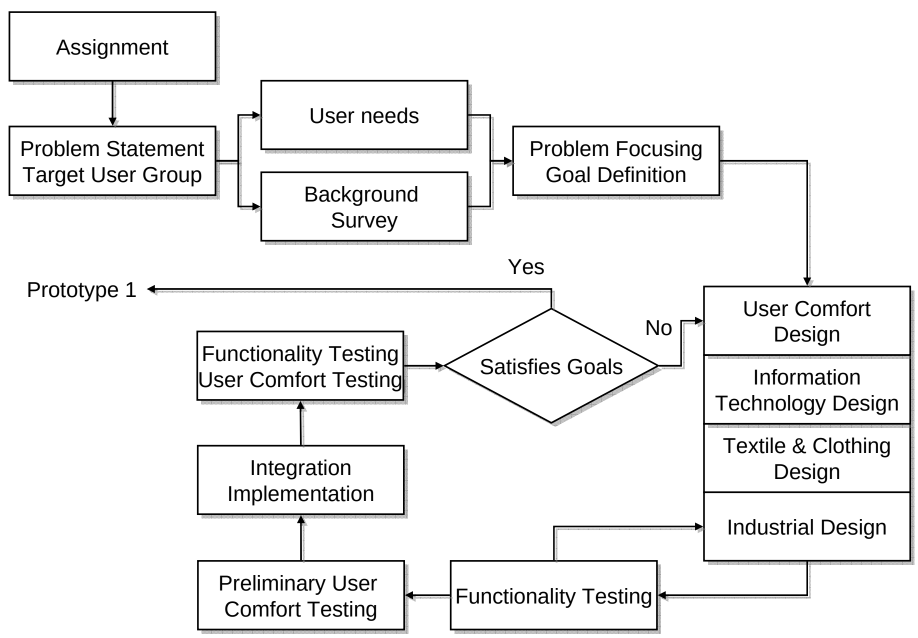

Figure 3. Smart clothing design flow.

planned to continue the development. After the first prototype has been designed, implemented, and evaluated, the next prototype generation starts by defining a new goal and continuing the loop as presented in Figure 3. The process described above aims at the development of the research prototypes. However, if the goal is commercial product implementation, other elements must also be considered in the process along side other sub-design issues. Such elements include manufacturability, consumer culture and associated aesthetics, and recycling [129]

3.2 Smart Clothing Design Requirements

Smart clothing application designers decide on the functionality of the applications according to a number of factors such as assignments and potential end user needs. This functionality greatly affects the users' decisions to adopt the applications. However, functionality is not the only measure by which to evaluate the importance of the application in question. Parameters affecting the application and its acceptance are presented in Figure 4, which is applied from [150].

First, functionality provides solutions to the problems for which the application is intended. This functionality is different in each application, at the same time varying the complexity of the system. The rest of the parameters are attributes of the functionality and are always present in different forms.

For the most part, performance attributes describe the efficiency of the system's

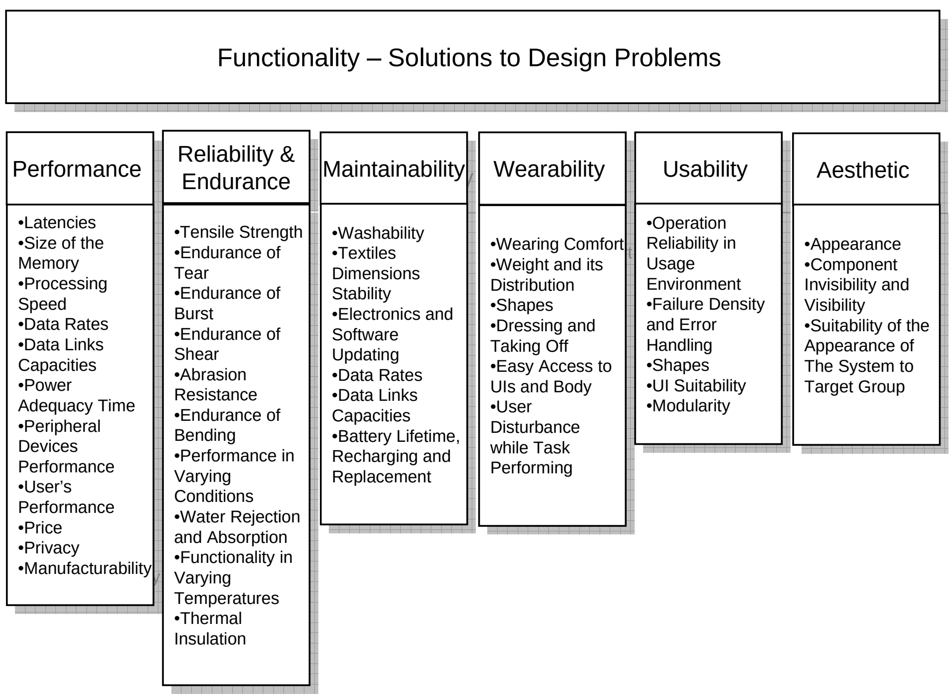

Figure 4. Parameters affecting the acceptance of the application.

electronics. However, smart clothing forms an integrated complex and, therefore, it is difficult to divide attributes for clothing and electronics into discrete parts. Depending on the application, the requirements for system performance varies. However, it is usually possible to measure the system according to its latencies in measurements and actuation, size of memory, processing speed, latencies of functions, data rates, data link capacities, data transfer latencies, power adequacy time, and other performance metrics depending on the peripheral devices needed in the functionality implementation [P8, 150, 176]. In addition, size, shape, and weight affect the way in which the system is used and, therefore, the user's performance with the system. For users, price and privacy protection are also important considerations and while production issues, such as the manufacturability of the system, are of major importance [150].

Reliability and endurance apply to both clothing and electronics, especially their mechanical robustness in use. For clothing materials, a variety of tests can be made to determine such properties as tensile strength, their endurance of tear, burst, and shear as well as abrasion resistance in order to estimate durability in usage conditions [210]. On the basis of these results, good quality materials can be selected for clothing applications. These same properties are also essential in the electronics placed into clothing. In clothing, especially, different connections are subjected to severe stress and, therefore, tensile strength plays an essential role as well as robustness against bending and abrasion. Performance under different conditions is common to both clothing and electronics. The abilities of materials to absorb or repel water are important since additional moisture may cause corrosion and unreliable functioning of electronics. Electronics functionality in different temperatures must be assured and the thermal insulating capacity of textiles is essential, especially in cold environments.

Maintainability of the clothing involves care procedures such as cleaning. This covers issues such as washability, parts need to be detached during washing, and behavior after washing such as textiles shrinking and dimension stability properties [9, 150]. Other important issues to be dealt with are electronics and software updating possibilities, battery lifetime, recharging, and replacement, as well as maintenance of the entire system before the smart clothing applications reach the market.

Wearability relates to the wearing of smart clothing and involves such issues as comfort, weight and its distribution, shape, ease of dress and undress. Other importance aspects of wearabilty are easy access to the body and user interfaces, as well as interference while performing other tasks [52, 150]. Wearability is closely related to the usability of the system in the target environment. It includes electronics and clothing operation reliability in usage conditions, failure density and error handling, UI suitability for the target group and the surrounding conditions, and modularity of the overall system [103]. Electrical characteristics such as Electrical Static Discharge (ESD) protection and ElectroMagnetic Interference (EMI) resistance affect the reliability of functions in desired conditions. The capacity of the clothing to transport moisture away from the skin area or protecting the user from rain, are examples of clothing characteristics affecting wearing comfort and usability.

The last attribute is the aesthetics, which describes the appearance or attractiveness of the clothing [9]. This concept indicates, for example, how well the design can conceal unwanted additional parts and what makes the look interesting in expressing the smart clothing concept to users [S1]. Cultural appearance of the clothing affects its suitability to the target group and the community. The appearance of the wearable systems also has a major impact on the general acceptability of the system [65, 177]. Small gadget-type devices can make the transition from tools to clothing accessories easier.

3.2.1 Characteristics of Mobility

Mobility is typically regarded as an attribute related to the portability of the electronics systems or the user's ability to move with devices between different locations [54]. The way of utilizing wearable devices also means that the interaction between wearable systems and users must be considered in this context. Such requirements can, therefore, be described by two categories: those for mobile devices in general, and those for mobile users and the interactions between users and devices while moving.

Mobility characterizes the systems in terms of power requirements, form factors, and usability [137, 207]. The form factor relates to the size, weight, and shape of the system and their interrelation, as well as the way in which the system is worn or carried [137, 220]. For mobile systems, the basic features are small size and low weight since usage should not impede the user or cause discomfort. Low-power functioning is also essential since power sources are often the bulkiest and heaviest parts of the system [181]. Typical power saving procedures involve the use of low-power components, setting unnecessary component modules to power saving modes when not needed, and performing computing at slower speeds [125]. It is also necessary to reduce the peak power of systems to increase battery life since the most typical energy sources utilized in wearable systems are secondary batteries [125].

Users' requirements are determined by the environment and the activities being undertaken [54]. Typically, users are concentrating on other tasks and mobile applications are utilized only intermittently. This means that users' visual channels are focused on several tasks at a time, hands are occupied with other tasks, and users are moving while utilizing the wearable applications. Such multi-tasking sets special requirements for UI devices. They need to be simple, intuitive, and easy to use, as well as capable of being operated with one hand or hands free [11, 137]. For the same reason, UI devices are typically distributed to suitable places on the body area for easy access. The hardware of UI devices needs to be simple enough with adequate tolerances between different buttons or switches so that minor aiming errors with the fingers do not impede usage. Feedback from actions also needs to utilize other sensory channels in addition to the visual in order to avoid overloading [220].

3.2.2 Requirements for Electronics Design

The usage environment for smart clothing is mobile, which means that users move indoors, outdoors, and from one to the other [113]. Regardless of the specific wearable electronics application environment, in comparison with office computing environments, the mobile environment poses greater challenges for electronics design. This is due to a variety of environmental factors, such as changing temperatures and humidity and means that the usage environment is more diversified than for desktop or laptop computers. Therefore, electronics need to be protected against adverse environmental conditions with suitable encasings that withstand a wide range of weather conditions such as cold and rain if needed.

Electrical power in smart clothes is utilized near the human body. Therefore, special attention needs to be paid to safety issues so that faults pose no danger to the user. Smart clothing applications are intended to be fully integrated systems, in which clothing and electronics are indistinguishable. At the moment, however, not all electronics withstand washing and so a good solution is to construct modular systems that can be utilized in different platforms and use components that can be easily replaced.

Modularity of the wearable electronics system is a key requirement when targeting the same concepts for several user groups. This requirement applies to the hardware part, which allows users to connect different functional modules to form an assembly and also to the software part, which needs to adjust to changing environments and hardware configurations [100]. Even in the same user group, those users who have been able to adjust the functionality and UI according to their own preferences will adapt to new techniques more easily than others [65].

3.2.3 Requirements for Clothing Design

The reasons for wearing clothes are defined as protection, modesty and privacy, status, identification, self-adornment, and self-expression [9]. Smart clothing applications are integrated into clothing. As a result, smart clothes also need to maintain the properties of clothing. Thus, clothing-like elements are utilized as often as possible in smart clothing application implementations [29, 40, 80]. These include soft and flexible wiring, thin and flexible Printed Wiring Boards (PWBs), and clothing-like connector elements. At present, smart clothing applications containing electronics need to be taken off for washing. Suitable materials are available for electronics protection, but this will add to the cost of systems. In addition, these materials do not protect clothing or additional components from the mechanical strains they undergo in a washing machine.

Comfort has generally been related to ergonomics in the workplace, for example thermal and visual comfort, and is defined as freedom from discomfort and pain [9, 86]. Textile materials in clothing affect users' thermal, tactile, and visual sensations [14]. This means that materials affect the user's perception of comfort. Elements in the sensation of comfort involve the emotions, the physical feel of the device, physical effects, feelings of being different, the way in which the device affects movement, and apprehensions about the device [86]. Emotions refer to users' concerns about their appearance while using the device and are related to emotions of unease, whereas feelings of being different reflect feelings of becoming different while using the device. The physical feel of the device is related to the way in which the device is attached to the body and the physical effects are the harm or damage that the system might cause to the body. Device-affecting movements are related to a user's way of moving while wearing the system. Worries concerning the device refer to a user's feelings about the device and its safety and reliability, which affect the user's emotions, such as anxiety. According to these six attributes, the overall comfort of the system can be measured and the causes of discomfort identified. However, other research also suggests that people can manipulate perceived comfort [19]. The form of smart clothing systems and their perceived functionality both have an important bearing on the user's readiness to accept the systems as suitable for the task in question.

Thermal comfort is the user's perception of the thermal environment [43]. In thermal comfort conditions the individual is unaware whether a lower or higher temperature is preferable to the current temperature. In addition, no part of the body is either too hot or too cold. Personal parameters such as clothing and environment characteristics have an effect on achieving the thermal comfort condition. For the wearer, the most effective way to influence this is to control the amount, quality, and type of the clothes worn.

Mathematically, a human heat balance equation can be utilized to estimate the thermal comfort condition. The heat balance equation describes how well the body can maintain its internal temperature at around 37 ºC in terms of internal heat generation and heat exchange with the environment [151]. Air temperature, radiant temperature, humidity, and air movement are the four basic environmental parameters affecting the responses of the human body in thermal environments. Together with metabolic heat generation and thermal resistance of the clothing, the environmental parameters form six fundamental factors that define human thermal environments to which humans respond [43, 151]. The heat balance equation according to Fanger [43] is given as

$$H - E_d - E_{sw} - E_{re} - L = K = R + C \quad , \tag{1}$$

where
H is the internal heat production in the human body,
E_d is the heat loss by water vapor diffusion through the skin,
E_{sw} is the heat loss by evaporation of sweat from the skin,
E_{re} is the latent respiration heat loss,
L is the dry respiration heat loss,
K is the heat transfer from the skin through the clothing,
R is the heat loss by radiation from the surface of the clothing, and
C is the heat loss by convection from the surface of the clothing.

The amount of released energy from the body depends on the activity level of the person, being the smallest at rest and increasing according to level of effort of the activity. This additional heat is then transferred from the body by evaporation, radiation, convection, and through the respiration channel. From the heat balance equation it is possible to conclude that the internal heat production reduced by heat loss due to evaporation and respiration should equal the heat loss through radiation and convection in the heat balance situation.

Social aspects of different wearable systems are often ignored, especially in the early stages. However, appearance is an important aspect of clothing and also a medium for communication [14]. People can utilize clothing for self-expression. The term *cyborg* to refer to a wearable electronics user is often derived from utilization of a wearable electronics system that is awkward, bulky, and heavy. Social acceptance is related to the ability of the apparatus to stand out and, therefore, it is also culture dependent [120].

Toney et al. employ the term "social weight" to describe the disturbance resulting from wearable electronics utilization in social interactions [201, 202]. Their approach is to integrate and embed wearable systems into business suits so that they are unobtrusive. UI devices are located in suitable places in the clothing so that the user can observe and use them without disrupting social activities, such as business meetings.

The appearance and comfort of wearable electronics can be influenced by the appropriate placement of components when linked to the dynamics of the human body [52]. A summary of design guidelines is presented in Table 1. Here the shapes, sizes, and weights of additional components as well as placements on the body are explained in terms of the moving human body, the functionality of the system, and individual components. When designing wearable systems suitable for as many wearers as possible, these guidelines make it easier to take account of different body sizes and shapes.

In the human body there are areas that are much the same size for every adult, non-moving, and having the largest surface areas. These are thus the most obvious locations to place additional components on the body. The shapes of additional components should follow the body contours, avoiding sharp edges that could damage the clothing and adversely affect social acceptance. Certain parts of the body such as the limbs also need to remain moveable after the addition of electronic or non-electronic components to the clothing. Therefore, it is recommended that additional components are placed on the body area. Wearers perceive this close proximity of components as being part of their own body. For individual sizing, alterations can be made at point to point distances and on rigid and flexible areas to achieve adjustments for different body sizes. Single point attachments on the body may cause discomfort and so additional components should be wrapped around the body and fitted with the necessary adjustments.

When designing encasings for the additional components, it should be considered if the component needs a contact to the surrounding environment or the user, such as for temperature measurements. The weight of the system should be minimized and most of the additional weight should be as close as possible to the body's center of gravity to limit the perception of the extra weight. In the design process, access during use to additional components such as UIs also needs to be considered. Therefore, components such as haptic feedback devices are located so that they can be felt on the body. Sensory interaction refers to the interaction issues between the wearable system and the user.

Table 1. Design guidelines for wearability [52].

Guideline	Explanation
Placement	Defines where additional components should go on the body
Form Language	Defines shapes for additional components
Human Movement	Consider parts in the body that need to be able to move
Proxemics	Perception of the size of the body
Sizing	Wearable systems should fit to as many users as possible
Attachment	Additional components fixing to the body in a comfortable way
Containment	Consider what is inside the form
Weight	Balancing the weight by distribution of additonal components to body
Accessibility	Physical access to additonal components
Sensory Interaction	Interaction between the user and the additonal components
Thermal Issues	Maintain thermal comfort of the user by proper component placement
Aesthetic	Appearance, perceptual appropriateness
Lon-term Use	Effects to the body and mind

This concerns almost all UIs. To achieve a good thermal comfort condition, components need to be located so that they cause no disruption to the natural heat exchange between the body and the environment. The field of wearable systems is still quite young and no research results are available on the long-term wearable usage effects on the human body or mind. This is an area for further research.

In addition, when considering the proper placement of additional components, locations on the body where people are accustomed to carrying devices can be exploited [162]. One such a place is the wrist where people are used to wearing watches, for example [124]. This placement is exploited for varies devices such as heart rate sensors and wrist-top computers for athletes. In addition, the apparatus is always accessible and thus instantly viewable, allowing physical access as well as interactions between the user and the device [52, 162]. However, devices need to be fairly small and light to fit comfortably on the wrist [188].

A basic rule for bulky wearable electronics systems is to place the components at suitable locations in the clothing so that the weight is distributed and wearing the system is comfortable. Integrating components into the user's personal space (i.e. clothes) decrease torque of components, allows systems to have the normal appearance of clothing, and promote the reliable functioning of certain components for such purposes as physiological signal measurement [S1, 52, 118].

3.2.4 Usability

The definition of usability varies within the literature. However, it relates to users, users’ tasks and tools, and the environment [103]. Usability and the overall acceptance of the system are interconnected as shown in Figure 5 [139]. The overall acceptability of the system is divided into social acceptability and practical acceptability. In wearable applications, the term “social acceptance” can be utilized to describe both the ethical aspects of the application as well as aspects concerning the appearance of the system. Usefulness defines whether the system can be utilized to achieve the desired goals. Utility defines whether the functionality of the system can solve specific problems, whereas usability measures how well users can make use of that functionality.

According to Nielsen, usability can be defined in terms of five attributes: learnability, effective use, memorability, error handling, and subjective satisfaction [139]. Learnability means how easy the system is to learn while effective use is how effective and well the system can be utilized once the usage has been learned. Memorability describes how easy the system is to use after periods out of use. Errors actually take two forms. Clearly systems should function with a minimum amount of error. However, when errors do occur, the quality of the system is defined according to its capability to recover and handle error situations. Subjective satisfaction is a qualitative measure of how different individuals experience the usage of the system.

There are several advantages resulting from a consideration of usability in the design of systems and applications. The needs of potential users for products and applications will be more easily identified. Usability tests can verify whether the system fulfils set requirements and whether it is suitable for its designated purpose. Significant savings in cost can be achieved when systems and applications function properly and reduce the need for maintenance, support, and repair [139]. In addition, the productivity of workers may be an issue since they can work more effectively and derive more satisfaction from the tools they use. Usability evaluations can be made at different times and stages during the design process. The purpose of these evaluations is to help designers to understand actual needs, compare competing designs and discover the best solutions to problems, to check the value of the design, and to ensure that the design conforms to any required standards [160].

The basic requirement for wearable electronics systems is that they can be utilized anywhere and anytime or in application-specific situations. This also means that UI devices are utilized in diverse environments and situations. When performing usability evaluations this feature also needs to be considered.

During the history of wearable systems, usability and the differing requirements for the systems have been recognized. However, little attention has been paid to the evaluation of the usability implication of long-term wearable electronics usage. Lyons and Starner have suggested a mobile recording device for wearable users, which enables capture of the user context by analyzing the interaction between the user and the machine. This is achieved by a video recording of the display that the user sees and by utilizing software that logs events generated by different applications [109]. This is also a common procedure utilized in desktop usability testing. In addition to this, they propose additional context sensing to find out what users see or hear during usage of wearable systems.

Design guidelines that affect usability are a concept model, visibility, mappings, feedback, and errors [141]. The concept model is related to systems functionality, design, and appearance. These three issues need to be in line so that users actually fully understand how to use the system and for what purpose the system is intended. If the functionality is explained to users they will have a better idea of the kind of design and appearance the system should have. According to their own perceptions as well as the

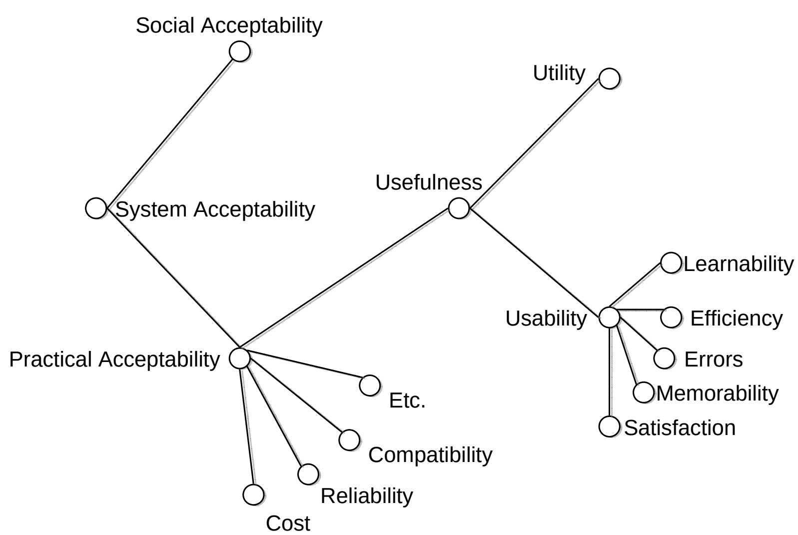

Figure 5. Overall acceptance of the system [139].

actual shape, size, and the appearance of the system, users can categorize the system's applicability into different tasks [19].

Visibility, feedback, and mappings relate to the usage of the system. Functionality needs to be transparent so that users can discover what they can do with the system. Feedback is needed to indicate to users that the system is actually working. Mappings refer to connections between controls and actions. Users need to receive help from this relationship so that control can be achieved without the instruction manual. In error situations there should be messages to users from the error source so that users can react appropriately.

Usability is a quality measure of the system and can be evaluated employing several methods, such as interviews, questionnaires, observations, and heuristic evaluations [103]. These evaluations are typically carried out on finished products and are known as summative evaluations [160]. Evaluations utilized at the beginning or during the design process are considered formative in nature because the results of these tests can be used to improve the design [160].

Perhaps the most common usability evaluation method is the usability test. In such testing, a selected group of users performs predesignated tasks in a laboratory or in the actual intended usage environment of the system. Test performance is either observed directly by the test makers or indirectly by utilizing video or audio recording. Typically a think-aloud protocol is utilized, in which testers verbally express their thinking while performing the tasks [160]. This helps in the identification of problematic situations and the reasons for them. In addition to usability tests, interviews and questionnaires may often be utilized to elicit information such as relevant background data and users' personal experiences and opinions.

In this thesis, usability or user acceptance evaluations are performed in [P1, P3, P4, P6, P7]. All the evaluated systems are prototypes and so the tests are regarded as being formative. Typical usability test procedure is illustrated in Figure 6. First, the goals of

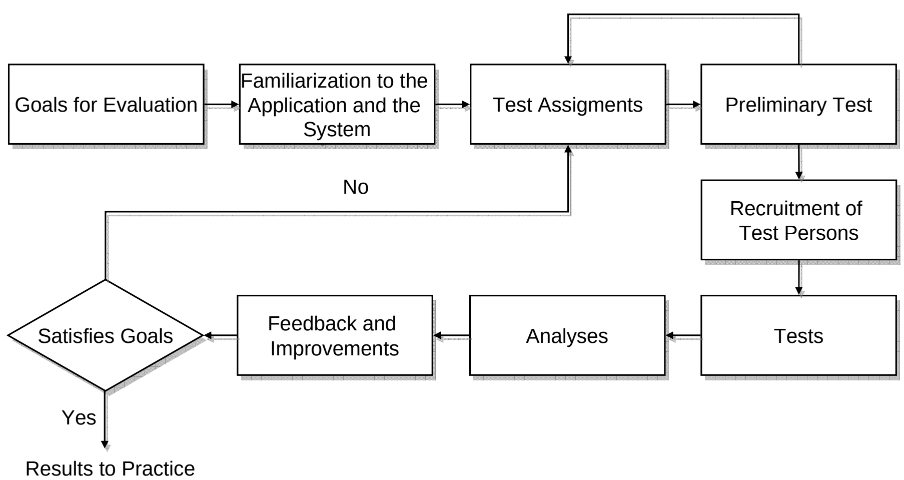

Figure 6. Typical usability test procedure.

the tests need to be specified. Second, testers need become familiar with the test subject and its functionality. After this the test assignments can be set.

Usability tests should include typical, critical, and potentially problematic tasks [103]. Typical tasks are performed on the basic functionality of the system. Critical tasks are assignments that include a certain level of risk or danger when performed incorrectly. Potentially problematic tasks are tasks that have been identified as difficult during the familiarization procedure. One method of conducting these tasks is heuristic evaluation, in which (usually) usability experts evaluate the system and its strengths and weaknesses according to a heuristic rule set [103]. One such list is introduced by Nielsen [139].

Once the test assignments have been specified, a preliminary test is made to estimate the time needed and ensure the proper functioning of all equipment at the testing site. At this stage test assignments or test site arrangements can be revised if necessary. The testers should be end users representing the target group of the application. However, when testing research prototypes in practice, it is common to recruit individuals who are easily available. In the test situation, assistants are needed for activities such as observation and assisting the testers. Before starting the tests, it is important to explain why testers are needed as well as the test procedure. In addition, permission must be obtained from the testers for the recordings. It is also important to explain what will happen to the data collected on completion of the tests. In the test situations, testers perform their assignments utilizing think aloud protocol and assistance is provided only if needed.

After testing, the results are analyzed. Typically, usability tests provide qualitative information. However, the time taken in the performance of each task may give valuable information, such as differences between test persons as well identifying those tasks causing most problems for the testers. Results are shown anonymously. Findings of the tests can be categorized and improvements suggested. If the results satisfy the goals set for the tests, improvements can be implemented or in some cases, tests can be performed again with modified assignments.

Usability evaluation has become more important with the increase in the number of different electronics devices utilized. Not every system can be learned, so instead, the UI should be easy to use and provide enough help for the user to avoid the need for instructions or memorizing. In addition, usability is emphasized when systems are worn. In smart clothing applications, the user is surrounded by additional technology and therefore, topics such as wearing comfort and the overall ergonomics of the system are important issues. To elicit users' opinions on such topics, interviews or questionnaires are typically conducted to ascertain users' subjective feelings.

The method for considering usability from the outset of the design process is known as user centered design. One such a method is Contextual Design (CD), which utilizes data collected from customers as the base criteria for defining the functionality of the systems [16]. The CD method is also employed as a case study in [P5]. However, this process is somewhat complex and is, therefore, unsuitable for quick prototyping research.

3.3 Smart Clothing Concept Model

The smart clothing concept model is illustrated in Figure 7. In this model a human is at the center of the system and covered with clothing, electronics, and other additional components. Clothing in this model is divided into three layers, comprising an underwear layer, an intermediate layer, and an outerwear layer. Their functions are transporting perspiration away from the skin area and maintaining a comfortable interface between the skin and clothes, keeping the user warm, and protecting the user from environmental danger. In the same way, smart clothing architecture components can be classified into clothing layers according to both functionality and proximity requirements. In this model the underwear layer with the additional components corresponds to the skin layer in the smart clothing system. Similarly, the intermediate layer corresponds to an inner clothing layer and the outermost layer to an outer clothing layer [P8].

The skin layer is physically the closest layer to the human body and, therefore, electronics requiring direct contacts with the person are placed here. These typically include physiological measurement systems, especially sensing elements, and UI components, which need to be easily available. The amount of additional components in underwear is limited because of the light structure of the clothing [S5].

The inner clothing layer consists of intermediate clothing and additional components

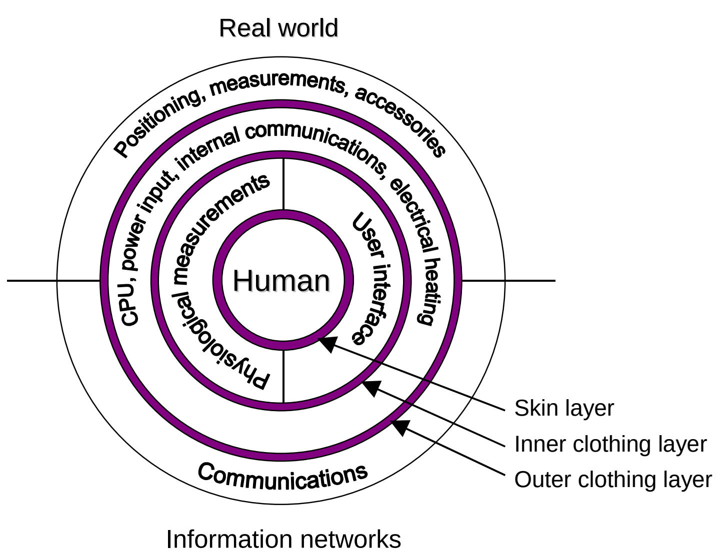

Figure 7. Smart clothing concept model.

that do not need skin or environment contacts. Components in this layer may be larger in size and heavier than the components in the skin layer. It is often beneficial to place components in this layer since they can be more easily concealed so as to give the appearance of ordinary clothing. In addition, the outerwear clothing layer provides shelter against adverse environmental conditions. Components in this layer contain devices such as CPUs, communication equipment, and power sources.

The outer clothing layer typically contains sensors to measure environmental parameters or equipment such as antennas for external or personal space communications. Additional components integrated into clothing accessories obviously belong to this layer. Smart clothing also provides an interface between users and their surroundings. It also acts as an interface between the application and the information networks that can be accessed by various communication technologies.

3.4 Smart Clothing Electronics Architecture

According to the smart clothing definition, sensing and actuation elements, data storage and processing, energy sources, and communication are all needed in every smart clothing application [P1, P2, 9, 153, 154, 165, 203]. Energy sources are needed to provide power for functions. Data storage and processing are needed for functionality and intelligence implementation. Sensors and actuators complete the control loop of the system. Communication is needed between the distributed components of the system, between the user and the system, between the system and information sources, and between the user and other people. A general smart clothing system is presented in Figure 8, containing the elements listed above. Inputs for the system are provided by the user or different sensors measuring the user or the environment. On the basis of such inputs and decision logic, the system gives feedback to the user and controls the performance of the automated functions.

Selection of the hardware components for smart clothing systems obviously depend on the application and the environment. This selection affects the reliability and endurance of the designed system, performance parameters, as well as maintainability issues. The electronics architecture of the smart clothing is illustrated Figure 9.

At the center of the design is a CPU, which is in responsible for the intelligence of the system. CPUs are often utilized as the central point of the design to connect the various electronics modules [P1]. For smart clothing applications, processor speed is not as critical as in general-purpose computers or desktop computers. Lower speed saves power. Functionality is also often more restricted, so that state-of-the-art clock speeds are unnecessary. In addition, the processor architecture can be distributed so that

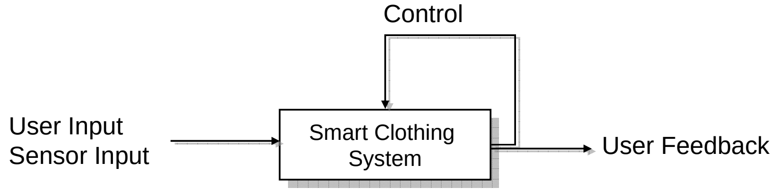

Figure 8. Smart clothing system.

processing occurs near the physical location where the information processing and calculation is needed. On the other hand, applications such as fully-functional wearable computers often utilize centralized CPU solutions.

Commercial wearable computer vendors are selling computers with 400 MHz and 500 MHz processing speeds [67, 226]. However, in smart clothing applications, small 8 to 16 bit microcontrollers are also commonly utilized [P1-P6]. In order to perform also more powerful tasks, solutions are needed to combine different task-specific processors [106]. Another approach for CPUs, is a PDA-based solution, which contains a display and processing capability in a same apparatus [P3-P5, 33].

3.4.1 Feedback Devices

The part-time usage of smart clothing while concentrating on other tasks may make usage of the display difficult. However, displays are the major feedback devices in desktop computing, and in wearable applications they also play a major role. People are accustomed to using displays so these are natural feedback devices in wearable electronics applications. Visual feedback devices utilized in wearable electronics applications can be basically divided to HMDs and panel type displays. The application and the data to be presented determine the type and characteristics of the display. HMDs can be utilized without interrupting work, however, they are not suitable for all tasks and so alternative feedback methods are also needed.

In wearable computers typically monocular, biocular, or binocular HMDs are integrated into the system for general-purpose usage [130, 182]. HMDs in the early stages of development were large in size and thus were not readily accepted [115]. In addition, in our own research with wearable computers in the late 1990s, the wire between the display and the CPU was often thick, causing some user discomfort [P8].

In wearable electronics applications, the basic requirement for the HMD is to be see-

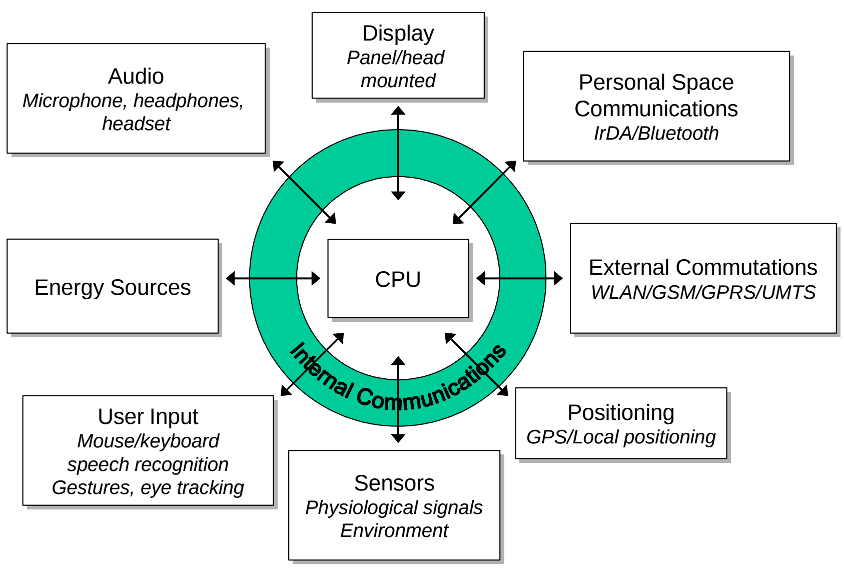

Figure 9. Smart clothing electronics architecture.

through. In the case of a non-see-through display, the display component should be for one eye only to allow unrestricted movement, uninterrupted performance of tasks, and AR applications. For long-term usage, HMDs should also be comfortable to wear [130, 205].

Displays are typically integrated into flexible fasteners, bands, or eye-glasses. For wearable electronics applications the latter is mostly utilized [85, 120, 179, 182]. For HMDs, Liquid Crystal Display (LCD) panels are typically utilized. However, other techniques such as picture direct painting to user's retina in Virtual Retinal Displays (VRDs) are also being investigated [133].

Even if today's HMDs are small and fairly unobtrusive, for a range of applications such as sport and physiological monitoring, these devices are still too conspicuous. Therefore, almost undetectable small display panels integrated in clothing or other feedback devices are widely utilized in wearable electronics applications as well.

PDA-based wearable solutions have the advantage of having the CPU and the display together in the same package. This is also the case with gadget-type wearable technology applications, such as heart rate monitors and wrist-worn computers, which have a display integrated on a wrist device [69, 70]. The display can also be integrated into other kinds of input device as with the Yo-Yo interface, utilized in the Cyberia project [P1, S1]. This is shown in Figure 10. This interface contains the feedback display and input methods in a same package. The menu picture on the display changes according to hand movements. In the menu, a user can make the desired selection by squeezing the display module.

In smart clothing applications displays can also be integrated into clothing. Examples of these are Light Emitting Diode (LED) displays on flexible substrates or optical fiber

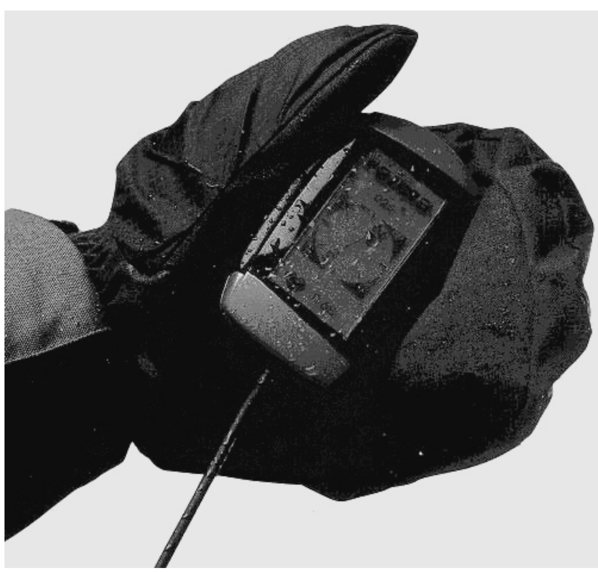

Figure 10. Yo-Yo interface.

technology combined with LEDs that can be utilized to achieve systems that maintain their clothing-like properties [88]. Projection displays have also been proposed, though these have the drawback that their information can also be read by others nearby [18]. New display technologies utilizing polymer fibers and benefiting from flexibility, probably represent the next important stage of development in smart clothing implementations [48].

A visual channel for feedback can also be utilized for simple notifications. LED integrated into clothing is a way of attracting the user's attention to notices [P1, S1]. Other typical feedback channels utilized are auditory and haptic channels. These are usually the channels employed when users have an impaired visual channel. However, in mobile environments, the visual channel may be overloaded and other channels need to be utilized. On the other hand, a user may be in a situation where some of their sensory channels are temporarily impaired as when walking in noisy and crowded places [51]. More than one feedback channel is, therefore, often necessary. Examples of auditory feedback are different sounds or speech [P1, S1, 170]. Typical haptic feedback systems are small tactors integrated at different locations in clothing [P5, P6, S3, 41, 194].

3.4.2 Input Methods

Conventional input devices, such as QWERTY keyboard and mouse, are unsuitable for mobile devices. This is because their usage needs space and are, in themselves, too large to be utilized or worn while moving. Therefore, alternative input devices or methods are typically utilized in smart clothing applications. These include simple switches and clothing-like keyboards, as well as speech and gesture inputs [P6, 131, 144, 164, 175]. However, usage of these new devices requires training, since people are familiar with the QWERTY keyboard and the mouse [198]. An example of a clothing-like touch sensitive switch is shown in Figure 11. When the user touches the switch with a finger, an electric current passes through skin between the metal sleeve and the ECF yarn around the sleeve. This is an example of very simple ON/OFF type functioning. N-Fingers is another example of an alternative input device for wearable applications utilized for selection tasks [99]. In one hand there are four mechanical buttons attached to finger joints, two in the middle finger and one in both the ring finger and the thumb. These buttons can be operated by the thumb and they function as arrow keys or have application-specific commands.

Since QWERTY keyboard is familiar to most people, miniaturized QWERTY keyboards and half-QWERTY keyboards are also utilized for wearable computer applications as primary text entry devices [127, 198]. These keyboards are typically fastened to the user's wrist and operated with the other hand. Such devices actually require two-handed operation and are, therefore, not practical for all applications. Performance of the QWERTY keyboards utilized with one hand for typing is significantly inferior to two-handed use [152]. Half-QWERTY keyboards dispense with the infrequently utilized keys and two letters are typed with the same key. The reduced number of keys and smaller keyboard make it usable when worn on the wrist [127].

In PDAs the commonly used input methods are touch screens, which enable hand-writing recognition or virtual keyboard usage as well as pointing device usage [24, 105, 229]. However, these input methods still require the use of both hands. For virtual

Figure 11. Example of clothing-like UI switch.

keyboards, alternative optimized layouts for letters are also implemented to promote more effective text entry [110, 229].

Typical keyboards for wearable computer usage are chordic keyboards, which are utilized by pressing several keys at the same time [108]. With such devices far fewer keys are needed than in QWERTY keyboards and these devices can be utilized with only one hand and in different positions.

Alternative user inputs are often related to body-based methods. These refer to UIs, which utilize the human body in pointing, feeding, or receiving feedback. Examples of these kinds of input devices are data gloves or a light glove, which allow direct pointing, selecting, or feeding using hand, wrist, and finger movements as well as posture [22, 47, 49, 72].

In addition, speech, eye movements, facial expressions, and emotions can be utilized for data inputting. Speech input is regarded as an effective input method since it does not have the scalability problem that almost every physical input device has and it is a very natural method for people [170]. In addition, both hands are free for other tasks [175]. Unfortunately, in practice it has suffered problems such as being user-dependent and most functional for short clearly distinctive controls. Eye gaze is typically utilized for computer usage when other methods are not possible, such as in the case of quadriplegia.

Physiological signals are natural inputs for computer systems and can be utilized for health monitoring as well as for implicit inputs. These inputs can trigger automatic help-calls or registration of situations in various user states. This latter group includes interpretation of a user's emotions. Emotion recognition systems are utilized in Human Computer Interaction (HCI) research to record the frustration or interests levels of users by means of inputs to the computer [61, 63]. Although many of these systems are intended for stationary use, it would also be reasonable to make them wearable. Affective computer systems are implemented by equipping the computer with suitable sensors to measure physiological parameters and tools to interpret the measured values

[156]. Therefore, clothing provides the necessary proximity and privacy for measurement implementations.

Virtual pockets represent a wearable user interface that can be distributed to several locations on clothing [98]. Each location hides pieces of information or computing objects, in the same way as conventional pockets conceal objects that may later be needed and allow the user access to storage when needed. UI hardware is implemented using clothing-like pressure sensitive textiles. These clothing-like materials are utilized for key implementations in snowboard clothing and denim jackets [158, 161, 211]. The advantage is that the input device is integrated into the clothing and, therefore, will not get lost. In addition, these input devices are washable.

3.4.3 Positioning

Positioning methods are technologies needed in wearable electronics design and implementation in several navigation and guidance applications, as well as in context-aware systems. Positioning techniques can be categorized according to accuracy, reliability, availability, latency, and suitability to the application in question [192]. The latter category includes power consumption, hardware size, weight, and shape, as well as dependency on infrastructure in the environment. In addition, different positioning methods are applicable in different environments. Another possibility to classify positioning methods is based on the location-sensing techniques. Three principal techniques are triangulation, scene analysis, and proximity [66].

For outdoor positioning, satellite-based techniques are the mostly commonly utilized due to their global availability. At present satellite positioning actually means the usage of GPS services. There are many commercial handheld GPS devices available for various purposes such as motoring, hunting, and trekking. These devices are nowadays small enough to be easily portable and enable wayfinding without additional infrastructure. However, for indoor positioning GPS is not suitable. This is due to its weak signal strength and, in urban areas, large buildings may block the signal between the satellite and the user’s receiver [192]. Therefore, other positioning methods are also needed. For outdoors, cellular networks employing proximity principle can be utilized [66, 192]. In this method, a user in a range of one or more wireless cellular access points can be detected and his position estimated.

The major methods used for indoor positioning involve different RF solutions, utilizing Wireless Local Area Networks (WLANs) or Bluetooth for location detection [91, 138]. In addition to RF, infrared-based solutions are employed in location and messaging systems [75, 186]. Inertial positioning, utilizing acceleration sensors and gyroscopes, is also suitable for positioning and navigation applications. However, it is prone to drifting and requires regular calibration with other positioning methods [8, 10]. As a result, it is often utilized together with a supplementary positioning method such as GPS [66].

3.4.4 Communications

Communication in wearable applications is needed, firstly, to connect distributed components together in a piece of clothing, between UI devices and clothing, and between the separate items of clothing. This type of communication is regarded as internal communication in that it takes place within the user’s clothing and is in close

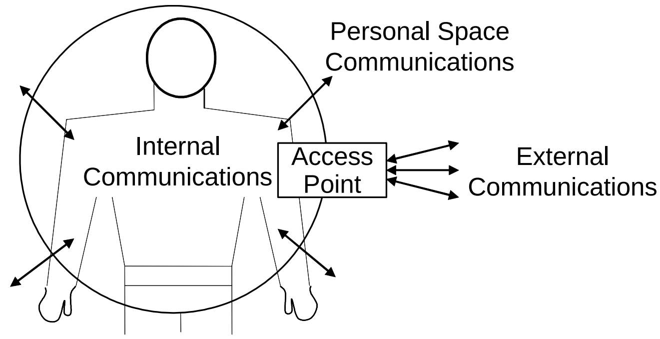

Figure 12. Communication layers in wearable electronics applications [P8].

proximity. Secondly, external communication is needed to data transfer between wearable systems and external information networks or other users. Thirdly, personal-space communication takes place when internal communication components initiate data transfer with the environment in an ad hoc manner. Personal-space communication is restricted to the user's close proximity, for example, data transfer between environment sensors and clothing. These communication layers are shown in Figure 12. In this general communication model for wearable electronics applications, there exists a single access point at a time to enable the external communication. This access point can, for example, be a network interface for a cellular data network. External communication can also be more easily managed because of this single access point.

For communication implementation, several techniques are available. The most suitable techniques are selected on the basis of communication needs which are determined by the types of data to be exchanged, data transfer rates, exchange periodicity, reliability, security, and cost, as well as power consumption. Different techniques are suitable for internal and external communication, and personal-space communication can be accomplished with a variety of techniques appropriate to the situation.

Communication techniques can be divided into wired and wireless data transfer techniques. Wired data transfer is practical only in internal communication in a piece of clothing. For this technique ordinary plastic insulated cables, ECF materials, or optical fibers are applicable. Ordinary cables are a straightforward solution, having high capacity. However, cables in clothes may tighten and, therefore, decrease user comfort [P1]. In addition, in cold environments cables typically become less flexible [P1]. ECF based yarns can also be utilized as cable replacements. They are strong, light, flexible, and clothing-like. However, there are, in practice, a few challenges in their usage [P9]. To benefit from the flexibility of fibers, ECFs need to be bare. This means that they are also electrically conductive on their surfaces. Another challenge is to have reliable connections between the ECF yarn and electronics. At present, optical fiber usage in clothing applications resembles sensor usage more than communication [97, 102].

Wireless communication techniques for low-range internal or personal space communications include the use of Radio Frequency (RF) modems, infrared, capacitive, ultrasound, and inductive communication techniques. Infrared communication is a simple and low-cost solution widely utilized in devices such as remote controllers, mobile phones, and portable computers. However, line-of-sight between a transmitter and a receiver is needed, which for practical purposes restricts the use of infrared communication to personal space communication. Capacitive coupling for close range applications has been used in wearable systems [159, 231]. In this communication method the human body is utilized as the information conduit. Ultrasound communication for data and power transfer has been proposed for implantable electronics data transfer between clothing and implants [4].

RFID is typically utilized in various tracking and identification applications. Several RFID systems work utilizing an inductive coupling principle. In active systems, separate power sources are needed both for a reader and a tag, whereas in passive systems a reader provides the necessary energy for a tag. In this latter case, communication is restricted to very short distances unless the size of the coupling element, the antenna, is increased. Fabric Area Network (FAN), which forms a network of inductive coupling elements, has been designed to overcome this problem [73]. Two adjacent nodes form the necessary coupling that allows the exchange of information between different items of clothing. Antenna elements can be made using soft fibers to achieve a clothing-like solution.

Low-range and low-power RF communication is suitable for internal as well as for personal-space communication [S6]. This communication method provides benefits over infrared communication since no line-of-sight is needed. Factors such as utilization on unlicensed Industrial, Scientific, Medical (ISM) bands and the availability of several low cost chips on the market have promoted their usage over other methods such as Bluetooth.

Several radiophone circuits are available for external communication in a range of between two to three kilometers. However, trunked radio network in a push-to-talk format enables an easy way for eavesdropping, which has restricted usage of this communication method [95]. Indoors, WLANs and Bluetooth technology are commonly utilized techniques for external communication. Coverage for both of these techniques is from 10 to 100 meters. However, for typical smart clothing applications where communication is between sensors in the environment and the user, these techniques are too powerful. Today, miniaturization of WLAN technology has advanced and WLANs are already integrated into devices such as smart phones. This trend suggests that their usage will extend into other areas such as smart clothing applications.

Wider range external communication utilizes Global System for Mobile communication (GSM), General Packet Radio System (GPRS), Enhanced Data rates for GSM Evolution (EDGE), or Universal Mobile Telecommunications System (UMTS), depending on the required data transfer rates. These techniques offer wide coverage and are actually the techniques needed for mobile systems to achieve continuous access to information networks while moving, for example, between home and office. For smart clothing applications however, Short Message Service (SMS) has been found to be practical for purposes such as varying controlling applications.

Antennas for wireless communication are not easily attached on the body. In satellite positioning systems, for example, the antenna should be placed so that the body will not block the incoming signal. Traditional antennas are hard components, which do not naturally integrate into the clothing structure. Planar antennas for unobtrusive clothing

Figure 13. Flexible antenna worn on front shoulder [P4].

integration have been proposed for GSM, UMTS, Bluetooth and WLANs [P11, S7, 168, 169]. In addition, flexible PWB or fabric antennas fit well into the clothing structure and increase user comfort.

Flexible PWB materials are generally considered the best solutions in clothing since they promote wearing comfort by adapting to the moving body. Furthermore, antennas are essential subparts of wireless communication systems, which are needed for personal space and external data transfer in smart clothing applications. Improper antenna design may increase transmission power dramatically and also increase the overall power consumption of the system. This is an undesirable feature for all mobile devices.

Flexible materials are lightweight and thin. These properties make it easier to place antennas utilizing these materials in clothing so that its appearance and properties are maintained. A flexible antenna suitable for Bluetooth communication has been investigated to replace wired data transfer between smart clothing and a desktop computer to make it easier to transmit measured sensor data to the computer for further analysis. Wearable antennas must be light-weight, small, and robust. Additionally, dual-band or multi-band operations are recommended to reduce the need for different antenna elements in clothing.

The designed antenna, worn on the front shoulder, is presented in Figure 13. The utilized antenna was found to be suitable for the clothing environment. However, in this application the placement and size of the antenna were such that rigid antenna materials could also have been utilized. Flexible antennas would be more beneficial if they were larger. However, in this application the most essential benefit was the weight of the antenna, which was less than that of a rigid PWB.

3.4.5 Energy sources

In mobile applications tetherless solutions are required. In addition to primary and secondary battery technologies, solar cells, and alternative energy harvesting methods are utilized [184, 186]. There have been many recent improvements in storage capacity, CPU speed, and data transfer speed. However, this is not the case with energy density development in batteries, which typically makes batteries the heaviest parts of wearable applications [181]. Improved power saving in hardware and software as well as alternative methods to power the systems is therefore needed. In mobile environments any additional weight can impair the usage comfort.

Primary batteries are typically utilized in very low-power applications [74]. However, such batteries need to be changed regularly, which makes usage more difficult. Secondary batteries are the most common solutions to power wearable applications. Typically Nickel-Metal-Hydride (NiMH), Lithium-ion (Li-ion), and Lithium-polymer (Li-polymer) batteries are utilized. NiMH batteries are safe and easy to use when prototyping, whereas lithium-based solutions offer better energy density [30, 60]. In addition, Li-polymer batteries make it possible to construct flexible batteries, which fit naturally into the clothing structure [206].

Energy harvesting from the user or the environment presently takes the form of kinetic energy from human movements. Shoes are an example of clothing platforms that provide space for additional components as well as an energy source from the steps. Energy from steps can be harvested using piezoelectric materials that produce electricity by the transformation of material under the sole or knee or by using mechanical rotary generators [93, 148, 184]. In addition, objects at different temperatures can be utilized for energy harvesting via heat transfer [148, 184]. This has been utilized to power such devices as wrist watches [148]. Solar cells can be manufactured in a flexible form and have been proposed as power sources for personal electronics devices [71, 221].

4 Prototype Smart Clothing Designs

Several research prototypes have been produced to find suitable ways to design and implement smart clothing applications. In addition to prototype designs, technologies relevant to clothing-like smart clothing design have been examined in detail.

4.1 Prototypes

The smart clothing prototypes designed and implemented are reported in [P1-P6]. [P7] deals with the usability tests performed for the CityGuide wearable electronics system.

4.1.1 Cyberia

The smart clothing prototype for the arctic environment is designed, implemented, and tested in [P1, P2, S1]. The starting point for the prototype implementation was to examine the possibilities of utilizing information technology, electronics, and advanced fiber and textile materials in the production of better functioning clothes. As a result, the project team included representatives from electronics and software engineering, fiber and textile engineering, clothing design, and industrial design. In addition, the concept of smart clothing and its subcomponents were also studied. The ultimate goal was to implement a full-scale application prototype which would embody the results of the project.

Since a Finnish clothing manufacturer specializing in sport and outdoor clothing was an initiator of the project, the obvious choice of application was one suited to their clothing range. As a result, a smart clothing prototype for the arctic environment was chosen with a special target group of snowmobile users. The reasons for this choice were fairly obvious since snowmobile clothing provides enough volume for additional intelligent embedding. It was also assumed that this target group would encounter the kind of risks that would provide the needed challenges to be overcome during the project. To avoid a false sense of safety and increase the risk level, it was decided that the target group should consist of experienced snowmobile users with basic survival and first aid skills as well as a basic knowledge of snowmobile repairs.

On the basis of a brief survey of snowmobile user accidents and target group user interviews, we put together a list of the challenges and problems for which we started to develop solutions. Seven problems were identified: getting lost, accidents, technical failure of the snowmobiles, changing weather conditions, health problems, lack of important equipment, and cold weather conditions. The challenge for the whole project group was to find solutions to these problems. The goal of the prototype was defined as the prevention of the type of accidents encountered in a cold and hazardous arctic environment. However, in the event of an accident, the prototype suit should aid survival for as long as possible.

In addition to the goals of the project, requirements were defined for the mobile application, user comfort, usability, and environment. Technical requirements for mobile computing were small size, low weight, and low-power operation. Therefore, the requirement for the extra weight was not to exceed one kilogram. The operation time of the system with one charge was specified as 24 hours. For maximum user comfort, the placement of additional components as well as their shapes and sizes were designed so as not to hamper the user or impair ordinary usage of the suit by applying guidelines from [52]. Requirements for the UI devices were that they should be well-suited to as many people as possible, suitable for both left- and right-handed persons, and capable of use with gloved hands. The cold environment was especially challenging for electronics design since every component should be functional in temperatures as low as minus 20°C to 50°C. The clothing should also adapt to changing weather conditions while also maintaining thermal comfort in extreme conditions. The electronics components should be able to withstand changing humidity and mechanical stress caused by typical usage conditions and the electronics attached in the clothing structure should be washable.

The survival suit prototype consists of a two-piece set of underwear, a supporting structure, and the actual snowmobile jacket and trousers. The electronic functionality of the suit can be divided into four parts: communication, navigation and positioning, user and environment monitoring, and heating. To maintain the appearance of ordinary clothing, the electronics modules were located in the supporting structure illustrated in Figure 14. This supporting structure is placed between the lining and coating of the jacket. Component placements in the structure were applied from [52] and verified using six volunteers of different body sizes. Weight was distributed along the body and the components were attached to the body with the structure to keep the weight as close to the center of the gravity as possible. The same structure can be adjusted to different body sizes. Hard and soft elements alternate to provide joints for movement. In the placement, the batteries are located at the warmest place to ensure their capacity in cold temperatures.

The functional architecture for the electronics is implemented utilizing GSM for communication, GPS and an electronic compass for navigation and positioning, and electrically heated conductive woven carbon fabric panels on the underwear's wrists for

Figure 14. Supporting structure and main electronics components [P2].

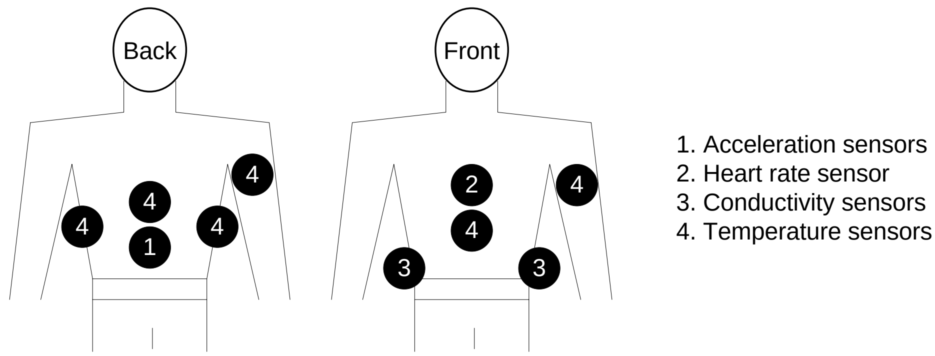

Figure 15. Sensor placements [P2].

heating. The user and the environment measurement system consist of a heart rate sensor, three position and movement sensors, ten temperature sensors, an electrical conductivity sensor, and two impact detection sensors. Placements of the sensors are shown in Figure 15. Low-power functioning guided the electronics design so that power saving modes were utilized and unnecessary usage of the system was avoided.

The external communication technology utilized GSM SMS as the suit was intended for use in Finland. SMS was chosen instead of the telephone to prevent needless use of the phone and to save power. For internal communication, ordinary cables suitable for a cold environment were used to connect the various electronics items. In addition, wireless inductive data transfer was utilized between the heart rate sensing elements and the receiver. In Finland there is a service providing weather forecasts on request, utilizing SMS. This solved the changing weather conditions problem since the user was able to obtain location-based weather forecasts by GSM SMS [P8].

Positioning and navigation was implemented utilizing GPS and a 3D (three dimensional) electric compass. With this functionality a user can navigate to a desired point, locate other suit users, and return along the route traveled. In addition, a special transparent map pocket was integrated onto the left thigh of the trousers. This positioning and navigation system was added to the system to overcome the problem of getting lost.

Electrical heating in the wrists of the suit's underwear was utilized for user heating only in the case of an accident. The reason for this is that electrical heating needs a great deal of energy and the batteries may quickly run down. Therefore, this heating option was possible only when there were no other options. In addition to heating, thermal equalizer phase changing material was utilized in the underwear. These were solutions for coping with the cold environment. In addition, such fabrics are examples of new textile material usage in clothing to improve its functionality. It was demonstrated that these materials are suitable for the clothing. However, for user comfort further research is needed to find ways of making more flexible and breathable designs.

User and environment measurements are utilized for the inputs to the decision logic. This is to support survival in three situations: heavy impact, falling into water, and injury. The measuring concept is illustrated in Figure 16. Measured signals are first

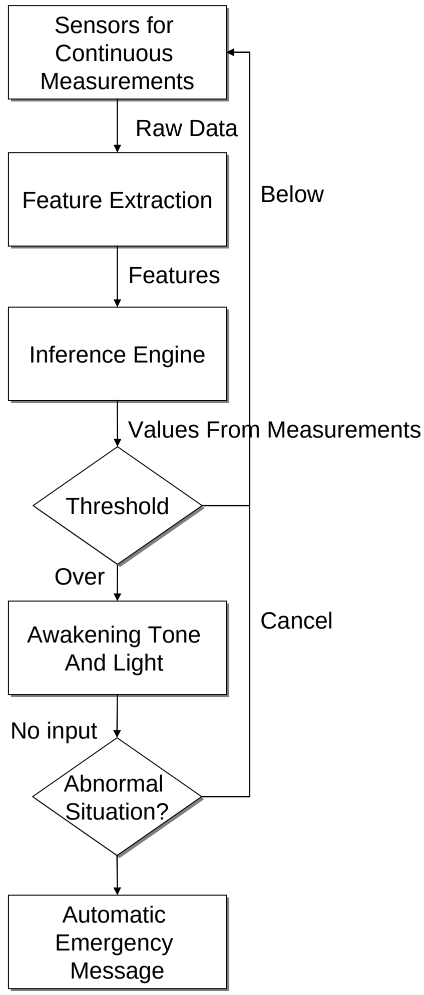

Figure 16. Cyberia measuring concept.

processed by a feature extraction system, in which all features are presented using binary values, where the condition is either true or false.

Acceleration sensors were utilized to detect sudden crashes and the position of the user. Five features are calculated from the outputs of the acceleration sensors. These features are rapid acceleration, the user is moving normally, the user has been immobile for a certain period, the user is in an upright position, and the user is lying down. Sensors are located on the CPU board at the small of the back as shown in Figure 15. This placement assures that any rapid acceleration measured, is only the result of an actual impact on the user. A heart rate sensor was utilized to measure vital functions. Three features are extracted from the heart rate signal: absence of heart beat, slow heart rate, and deviation of the heart rate signal below the normal level. A special electrical conductivity sensor indicates if the user has fallen through ice, in terms of whether or not the user is surrounded by the water. Temperature sensors are utilized to measure the user's microclimate temperature and outside air temperature. These sensor measurements show whether the user is lying on a cold surface or not. An inference engine is utilized to identify an abnormal situation on the basis of whether the predefined threshold value for any of the three situations is exceeded. These sensors, together with positioning and communication, were utilized to solve problems concerning health issues and accidents.

If the monitoring system recognizes any of these three abnormal situations, an automatic emergency message is sent by GSM SMS. Before sending the message, the suit informs the user by means of an audio signal and warning light and the user has one minute to cancel sending the message. This is a precaution against false alarms. If the user does not cancel the message, it is sent to a pre-selected phone number. This message contains an emergency reason code, which indicates either an injury or technical failure, and the current position of the user. After this message has been received, additional information concerning the sensor values can be requested from the suit. The user is also able to send an emergency message manually in the event of technical failure or minor health problems.

The lack of important equipment was solved by integrating non-electronic components such as ice spikes, a hypothermia bag, a snow melting pocket, fire kit, and a first aid kit into the suit. Non-electronic features of the suit are illustrated in Figure 17. Non-electronic functions integrated to smart clothing systems are highly application-dependent. In this project, it was noted that the integration of important equipment into the clothing structure could aid survival in actual situations. The addition of the non-electronic features to the suit was decided on the basis of likely problems and user scenarios. In addition to the non-electronic features, functional textile materials were also utilized in the design. These included, waterproof outerwear material, water and fireproof material for the snow melting pocket, conductive woven carbon fabric for electrical heating, thermal equalizer phase-changing material in the underwear, and ECF utilized in electrodes to measure heart rate. Among the valuable information obtained during the project was that materials are available that can improve the functionality of clothing. However, more research is needed to achieve both reliable functionality and wearing comfort.

After the suit was designed and implemented it was tested in actual conditions in Lapland. During testing user comfort and electrical functionality were evaluated. Since the suit was a prototype more emphasis was placed on wearability and the users' subjective feelings of the suit. The appearance of the suit was like that of an ordinary suit and the users were unaware of any lumps or bulges caused by the electronics. Therefore, the goal of implementing a full-scale smart clothing prototype having the appearance of ordinary clothing was successfully achieved.

The numerous cables needed for connecting the different electrical components together made the suit more inflexible, especially in tasks involving stretching. However, the additional components added to the system caused no problems or discomfort to the users. It can, therefore, be concluded that the placement of the components was successful. Technical functionality was tested by simulating problematic conditions and

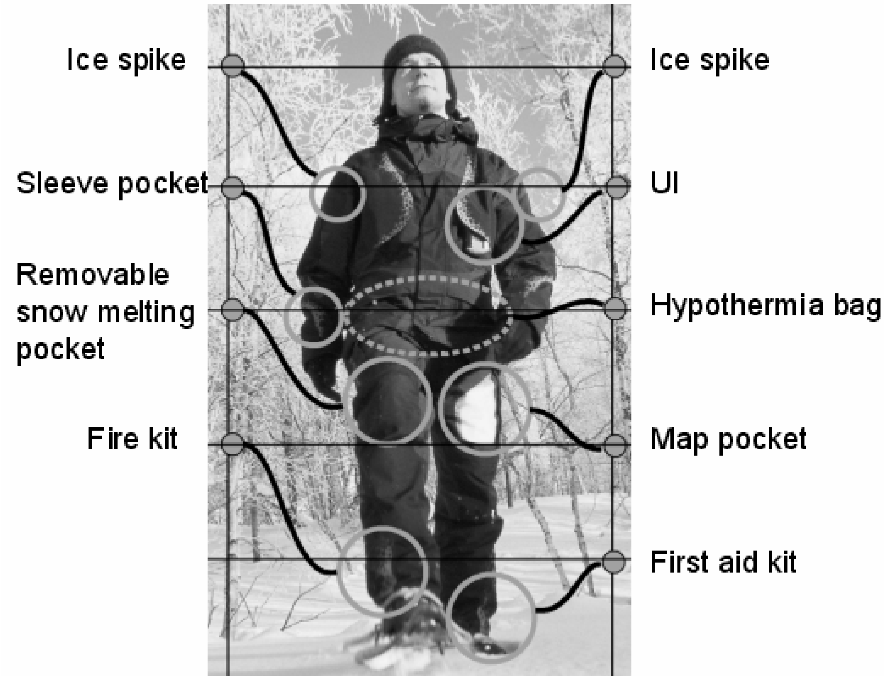

Figure 17. Non-electronic features of the Cyberia suit [P1].

verifying that alarm messages had been sent. The suit was found to be functional and the only problems were with the UI. The method of using the UI proved to be convenient, but usability was reduced when thick gloves or mittens were worn. This could have been improved using a smaller display unit, but no suitable display was available for the required temperature range on the commercial market. The connector cable of the Yo-Yo was very easily broken, causing connection problems. Not all the components used are suitable for the desired temperature range. Nevertheless, they are located in a warm place near the body in the supporting structure. Only the display showed any adverse effects in temperatures below minus 20 ºC by becoming very slow.

4.1.2 Electrically Heated Prototypes 1 and 2

According to the definition of smart clothing, smart clothes try to be better than ordinary ones. Therefore, the functionality of clothing to keep it users warm and maintain the thermal comfort of the user were investigated with the focus on functionality and usefulness [P1, P3, P4]. Since the place of work was conducted at the Institute of Electronics, electrical heating was the preferred solution to others such as chemical solutions. In addition, the material utilized for the heating implementation was found to be very potential solution is the previous research. The starting point for the research was the Cyberia suit, in which electrical heating was utilised in underwear wrists to keep the user warm in accident situations. In the Cyberia project conductive woven carbon fabric heating panels were used for heating implementation and it was decided to study the actual suitability of such panels for mobile applications. First, we implemented the electrically heated clothing utilizing an ordinary undershirt as the

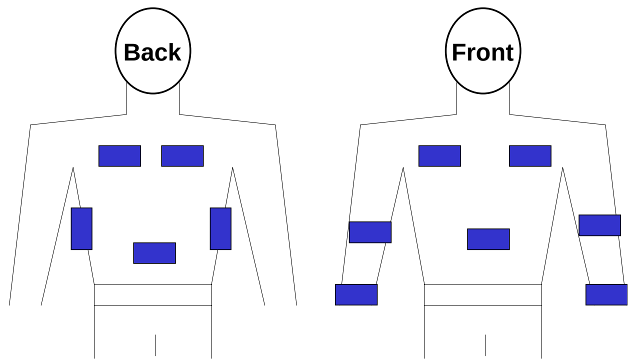

Figure 18. Location of heating panels on the undershirt [P3].

electronics platform. The goal was to improve the thermal balance of the user, rather than overheating the user. The shirt was chosen as the platform for the application because it was considered easier to utilize a single item of clothing for the initial testing of the principle. A tight-fitting shirt follows the line of the body and, therefore, additional heat has a direct effect on the body.

The design started with the specification of heating panels. Conductive woven carbon fabric is brittle and backing material was necessary. From the samples, material resembling thin foamed plastic was chosen due to its flexibility. This was thought to increase the wearing comfort. Next, the problem of the power consumption was solved by limiting the current to 750 mA with 12 V supply. In order to limit this current, the sizes of the heating panels were defined so that overall resistance was 16 Ω. To achieve this, each panel is 185 mm in width and 50 mm in height. Altogether twelve panels were sewn on the undershirt at the locations shown in Figure 18. Flat copper conductors with small connectors are sewn to both ends of the panels, which are attached to the shirt with Velcro tape. This allows small location changes of the panels and means they can be detached during washing of the shirt. This was necessary for this particular material, which was found to be too brittle for machine washing.

The heating prototype works by measuring the user's surface body temperatures with nine temperature sensors. Their placements, which are only on the upper body, are applied from ISO 9886 standard [78]. With the test UI, the wearer of the suit can set the desired temperature values for the body and arms. According to the measured temperatures and set values the controlling electronics calculate the necessary pulse widths for the heating. The greater the difference is between the set values and measured temperatures, the higher is the output power for heating. Before using the system, the user switches the system ON utilizing the UI and selects the power mode at half power or full. After this the heating is automatic. The controlling electronics are placed into the additional pockets on the back of the shirt, as shown in Figure 19. The components, with the exception of the batteries, are fastened to the undershirt. The batteries were too heavy for such a light structure as the undershirt. They are, therefore, fastened onto a separate belt, which is easy to put on and take off.

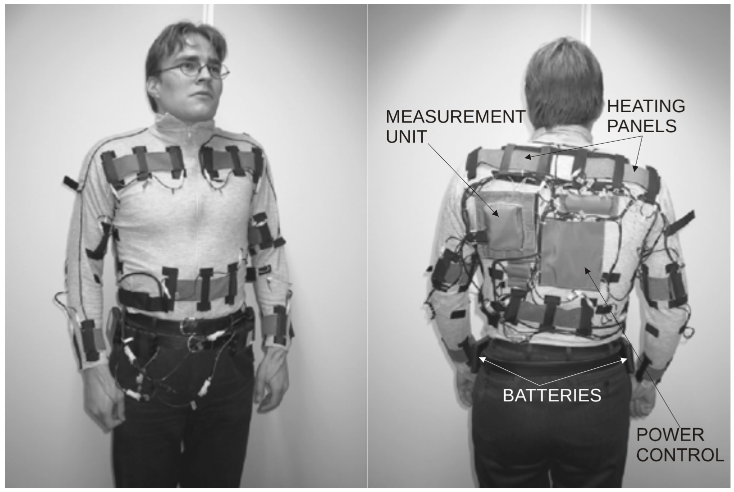

Figure 19. First heating prototype.

In addition to temperature sensors, three humidity sensors were added to the shirt for analysis purposes. The sensors are connected to the measurement unit, which performs the measurements. The power control unit takes care of heating power control. The power source comprises two separate NiMH battery packages providing 12 V input to the heating panels. With the test UI, which in this application was a pen-based PDA, the user can manually start and stop the heating, select the heating mode, start and stop the measurements, change set values for the heating, and transmit the measured data to the computer for further analysis. More detailed information on the electronics components in the application can be found in [S2].

Before the user acceptance tests, the functionality of the system was evaluated in the laboratory and one person also tested the shirt outdoors and made a subjective evaluation of the locations of the heating panels.

For the tests, ten university staff members and students were selected according to size, since only a medium size shirt was available. Tests were performed on the university campus area utilizing the heating shirt and a light overcoat. The testers were able to choose the rest of their clothing themselves. Heat generated by metabolism is mostly transported by convection from internal organs and muscles to the peripheral parts of limbs and skin. From the skin the heat is transferred to the surroundings by conduction, convention, radiation, and evaporation as well as through respiration [43]. In cold environments most heat loss takes place through uncovered head since the organs try to guarantee brain functions. In addition, badly covered peripheral parts of limbs are a path for heat loss. Therefore, the entire clothing affects the heat balance. However, in these tests entire clothing standardization was not possible.

Each test can be divided into three stages. First, the test person stands still for five minutes. Second, the test person and a test assistant walk slowly for a half-kilometer so that the heating is OFF. Third, the same route is walked again utilizing the heating

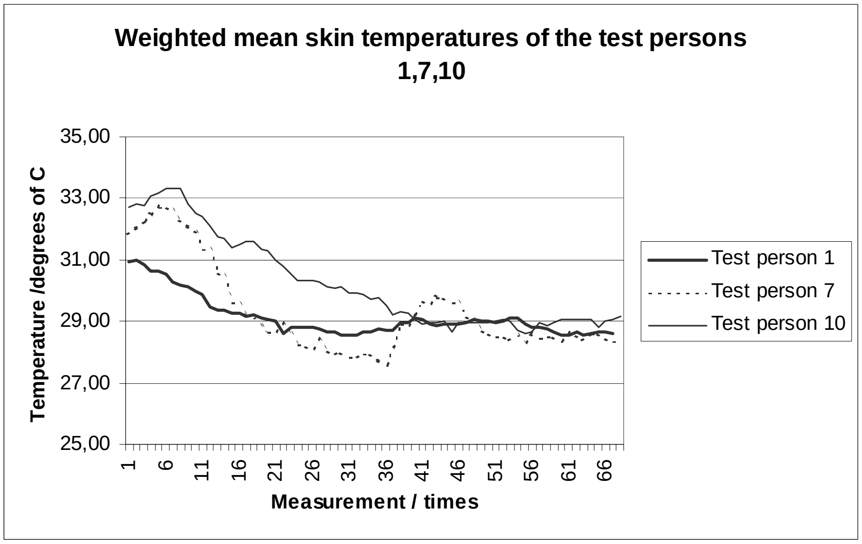

Figure 20. Behavior of skin temperatures of three test persons [P3].

option. This walking provided an estimation equivalent to performing light work. During the test, the test assistant asked questions about the wearer's thermal comfort and whether any part of the body was too hot or cold. The functionality of the system was analyzed on the basis of this data and the measured temperature and humidity values.

First, analyzes were made of temperature measurements. Obvious variations in temperature levels were found and it was, therefore, concluded that the system had measured microclimate temperatures instead of true surface temperatures. These temperature values started to decrease for each person while the heating was OFF. After switching the heating ON, temperature values behaved in three different ways as shown in Figure 20. These values show that the heating power utilized in the prototypes cannot increase the temperatures. However, temperature values just before the heating is turned ON can be maintained.

Heat losses for each test person were calculated according to (1), separately for both of the test rounds; firstly when heating was off and secondly when heating was on. It was found that the heating power theoretically could not maintain the heat balance. However, the measurement arrangement for radiation temperature measurements, for example, were not standardised and so these heat loss calculations can only be indicative.

The general view derived from the subjective evaluations of testers' thermal comfort conditions was that the heating power was inadequate. However, all the testers could feel the heating, especially in the upper back and arms. It was concluded, therefore, that the test users' expectations were too high since they expected the system to be hot. However, in a thermal comfort condition any part of the body should not be too hot and

Figure 21. Sensor shirt [P4].

so the approach of the research is correct. However, to achieve the overall thermal comfort condition, the whole body should have been heated.

Due to the somewhat unattractive appearance of the shirt and its decreased usage comfort, it was decided to improve the design by separating the heating and measurements into separate clothing layers, adapting the smart clothing concept model. The inner covering jacket illustrated in Figure 13 serves as a platform for the heating panels. Eleven panels are placed inside the jacket at areas around wrists, arms, shoulders, chest, and back. An undershirt similar to that in the first heating prototype is the platform for the sensors. These include nine temperature sensors, a skin conductivity sensor, and a respiration sensor. The additional electronics needed in the measurements are also placed in the undershirt. The undershirt is illustrated in Figure 21. The skin conductivity sensor and the respiration sensor are added to the shirt for analysis purposes. In this way a more reliable estimate can be made of the heaviness of the work that the application user is performing.

The undershirt is now constructed using more clothing-like elements than in the first prototype. The connector wires between the temperature sensors are replaced by electrically conductive metal clad aramid fiber yarn, which combines the conductivity of metals with the light weight and flexibility of aramid fibers. To prevent short circuits, the yarns are embedded into the wire channels. The same material is also utilized for skin conductivity electrodes. In practice, it was noticed that above and beyond the hard solder bonding, the yarn breaks easily. Therefore, silver doped electric conductive glue was utilized in connections. However, when in contact with other hard materials such as heat-shrinkable plastic tubes, the yarns still tend to break.

The second heating prototype was only tested indoors. Since the heating source is not as close to the skin as in the first prototype, potentially more power is needed for heating. It was noted in the first case that users felt the heating power was too low and the measurements were also similar. As a result, electrical heating implemented in this way is not considered practical for mobile applications. This is actually due to the weight of batteries and their capacity. With this configuration a user can be heated for only about half-hour. The usage comfort of the system was found to be much better than in the first case and the appearance was much more attractive. The latter is very important for users since in the first prototype implementation, some of test persons were alarmed by the shirt’s appearance.

The two prototypes implemented show that it is possible to implement electrical heating in clothing applications. In addition, users liked the idea of electrical heating in general. However, the appearance was found to be intimidating and the system was found to be too difficult to put on. In addition, the heating power was not adequate for users. It was also suggested that other items could be heated such as the thighs, which in winter often get cold while walking even short distances outside.

The first heating prototype implemented is an example of the wearable system, in which the design emphasis is on functionality implementation. Although the system itself was functional, the appearance was too clumsy for potential users despite the fact that test users were mostly technical people working with electronics. The approach adopted in wearable electronics systems design and implementations is often one of trial and error. It is, therefore, beneficial if the system is constructed in a modular way, making it easy to repair or replace parts of electrical components. In addition, such construction enables easy access to electronics and, therefore, helps in debugging. In terms of user acceptance of the application, it would have been better to perform testing with heating prototype 2. Nonetheless, the functionality and user acceptance tests were combined and the tests performed were very helpful in analyzing the overall functionality of the system.

4.1.3 Positioning – Personal Position Manager

Research into positioning capabilities focussed on the usability issues and wearing comfort of the wearable systems having distributed electronics architecture. Outdoor positioning was selected as a research target since no additional infrastructure construction is needed. At that time (2001-2002) potential technologies were the utilization of communication networks and satellite positioning. GPS was the most globally available technology and was, therefore, selected as the technology for the research prototype implementation [P5].

With the help of positioning new features can be given to clothing. In this prototype, electronics integration and distribution in clothing was the main goal. Commercially available clothes were first utilized as a platform. In this way more emphasis could be placed on proper and reliable functioning as well as easy usage of the system. After ensuring this first goal, a new prototype was constructed utilizing self-made clothing in which the focus was on the placements of the components. Feedback was also sought on the usability and the wearing comfort of the system. Thus, a case example was made of applying user centered design method to this application design. Due to the strict schedule of the project there was no time to make the components washable. Therefore, encasing materials to withstand washing were studied separately.

As a result of the positioning research, Personal Position Manager (PPM) vest was implemented. Fishing was selected as the target application. However, the same electronics in different clothing platform are suitable for a range of other applications, such as hiking or picking berries. Since the goal was to achieve an easy-to-use system for fishing, in which the environment might be very demanding with a range of weather conditions and temperatures, the whole function of the concept needed to be different from commercial gadget-type GPS devices. The possibility to utilize the system solely for marking coordinates of different locations while fishing were added to the system parallel to the typical usage of the PDA as a UI device. This also enables more complex functions such as navigation.

PPM consists of the clothing platform and additional electronics placed in the vest, application software for the microcontroller, and an additional PDA UI and its software. For the main function, namely positioning, a commercial GPS module was chosen. Requirements for the selection were availability, small size, low power consumption, a wide range of operating temperatures, and the possibility to use active and passive antenna solutions. The antenna of the system is placed on the shoulder of the vest, allowing a good line-of-sight to satellites.

PPM contains two different UIs. The UI switch is intended only for location marking. The UI switch is a touch-sensitive platform designed to be clothing-like, easy to use, and reliable. Since the system does not provide any mechanical feedback, vibrating feedback is added to the system. When the switch is touched gently the system saves the current location coordinates into the memory of the microcontroller board immediately, or saves the location until enough satellites are in sight. The PDA UI is intended for navigation tasks and for making additional notices. After saving a location to the memory of the system, the user can add a description of the place or other details, utilizing the PDA. The entire PPM system is illustrated in Figure 22.

The functionality of the system was first verified by one module at a time. After that the entire project group participated to user tests. This approach was selected because, according to the application specifications, we were unable to get actual end users. This preliminary evaluation actually focused on user comfort and UI switch functioning. Therefore, this user evaluation also served as the functional evaluation of the integrated system. In addition, the intention was to apply user centered design. Therefore, the approach to utilize the project team for identifying the major difficulties in usage was reasonable.

Figure 22. PPM vest.

During the user evaluation two major shortcomings were discovered. First, it was noticed that navigation was impossible in slow movements such as slow walking. This was because there was no compass in the system. To find the correct direction the user must be continually moving to enable direction corrections based on the previous coordinates. The second problem was due to the UI switch, which worked well indoors. In outdoor conditions, however, depending on the surrounding environment and electrical conductivity of the user's finger, touch was sometimes not recognized. Therefore, the sensitivity of the switch needs to be easily modifiable.

After the first PPM prototype was made, a CD method was also utilized to improve the functionality and user acceptance of the system. The target group consisted of five persons interested in fishing, mountain biking, and hiking. During this approach, the same drawbacks were noted as in the usability tests. In addition, it was recommended that the system should be modular and able to be utilized in different platforms. It was also noticed that the pen-based interface was difficult to use both indoors and outdoors and so the pen should be utilized only for selection. This led to the system utilizing maps instead of coordinates. With the pen, a user can select the next intended location. Additional information and description of the locations could then be made utilizing a speech interface. These were tested only with paper prototypes since the changes were too great to be implemented within the budget and time available.

During the design and implementation of this prototype, it was realized that the electronics are actually small and light enough to be integrated into clothing without additional miniaturization. For wearing comfort, no improvements were needed since the weight of the electronics did not disturb users at all. The only problem with the first prototype was that the pockets were full of electronics and could not be used by the wearer of the vest. Therefore, in the new prototype the electronics were placed between the outerwear material and lining so as not to inconvenience the user. Conventional ways of using clothing as well as application-specific UIs are needed. The test UI for demanding tasks was a commercial PDA, which is not suitable for field usage and should be replaced with a better solution in the final application. Despite the problems with the UI switch, it was a positive experience since in summer it worked properly for various people, without any need for sensitivity modification.

Three materials tested for the electronics encasings were bright silicone elastomer, black polyurethane resin, and polyester resin. Silicone elastomer is a flexible material and therefore considered a suitable material for clothing. However, at the sharp edges of the PWBs the material broke too easily. Polyurethane was found to be the best material tested as it was moisture proof. All the test boards were functional after climate chamber testing and water submersion. However, for encasings in prototypes, molding is not practical since in a non-functioning situation, the origin of the failure cannot be identified. Tests demonstrated that with the use of the proper materials, it is possible to seal electronics so that moisture will not reach the PWBs during submersion in water or washing with liquid agents. The test boards were also washed in a washing machine. However, the mechanical strain during machine washing may be hazardous for sensitive electronics.

Perhaps, the major lesson learned during this prototype implementation was that people are accustomed to utilize gadget-type devices. Therefore, these kinds of special integrated complexes were found to be impractical. People did not necessarily demand gadgets but instead thought that modular systems that can be utilized with different clothing platforms would be more useful. At present the best solution for this is to use one device, which can be hidden inside the pockets of clothes or accessories while fishing. Nonetheless, the application proved successful in that it caused no harm to the user, the switch UI was also easy to use even while performing other tasks, and the system has the appearance of ordinary clothing. The electronics were attached to the front of the vest between the lining and outerwear material. It was shown that the electronics were small, thin, and light enough to be integrated in this kind of clothing without impairing the wearing comfort. Electronics placement was applied from [52]. The UI switch was located at the front of the chest for easy access.

4.1.4 Bioimpedance Suit

Clothing is thought to be the ideal platform for the physiological measurements. To determine the opportunities and usefulness of integrating the physiological measurement systems into clothing, a bioimpedance measurement system was designed. Bioimpedance was chosen as an application because it is related to the amount of Total Body Water (TBW). This, in turn, is related to water balance, which is a critical factor in long term sports, where even a small decrease in water balance can weaken performance [P6].

The goals of the research were to design and implement a wearable prototype to study the integration of physiological monitoring systems into clothing. First, the system should be integrated into the clothing as well as possible so that it can also be utilized in

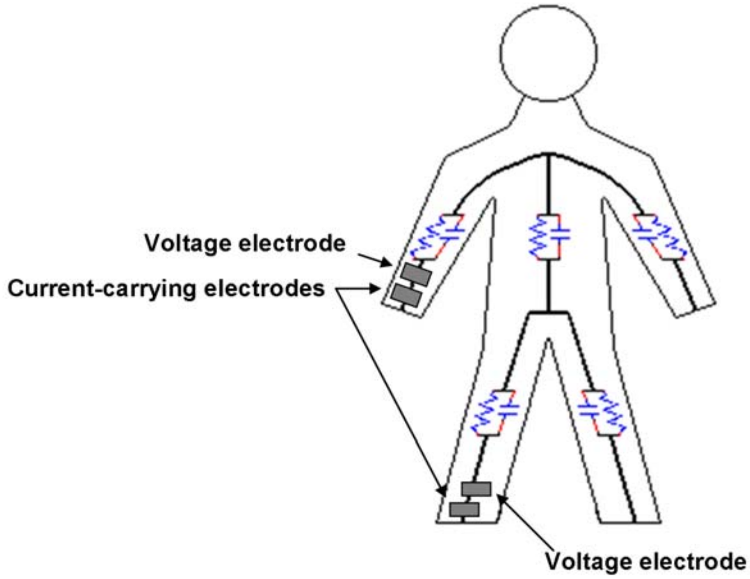

Figure 23. Electrode placement for bioimpedance measurements [P6].

physically demanding sports. Second, the reliability and applicability of textile electrodes were investigated and third, the suitability of the measurement concept for TBW estimation was determined.

Water content estimation in the body can be performed by estimating TBW, which can be calculated as

$$TBW = \frac{k}{R_P} \quad , \qquad (2)$$

where R_P is the parallel resistance in the human body and k is constant [57].

Naturally, the amount of TBW should decrease after exercising until sweating occurs. Water leaves the body as sweating and impedance of the body increases. For the bioimpedance measurements, a small current is fed through the body and voltage over the body is measured. The relation between the measured voltage and fed current is the bioimpedance. The human body can be modeled with five impedance segments as shown in Figure 23 [57]. In this research, the hand-to-foot configuration for electrode placements were chosen since it covers three segments and therefore models the whole body fairly well. The outer electrodes in Figure 23 are for current feeding to the body and the inner electrodes are utilized for voltage measurements.

The wearable bioimpedance measurement system is integrated into a sport suit to enable testing in actual environments. First, a commercial shell suit was utilized. After the first tests two custom suits were also made. Most of the electronics are integrated into the back of the jacket of the sport suit between the lining and the outerwear material. The UI is placed into the left sleeve of the jacket. In order to perform bioimpedance measurements there needs to be a galvanic connection between the electrodes and the

Figure 24. Bioimpedance measurement system [P6].

measurement electronics. Therefore, there are measurement wires from the electronics to the electrodes inside the jacket and trousers. The connections between the electrodes and the measurement wires are made using simple snap fasteners. The bioimpedance measurement suit and placements for the electronics are illustrated in Figure 24.

At present the functionality of the system is very simple. The user wears the system and turns it ON utilizing the ON/OFF switch. To start recording impedance values, the user starts the measurement utilizing push buttons on the sleeve of the jacket. Push buttons can be utilized to start and stop the measurements. Data from the impedance measurements are saved to the memory of the system and can be transferred to the computer for further analysis and TBW calculations. The UI in the measurement suit is designed to be as simple as possible. In addition to buttons and switches, there is also a vibrating motor, which provides feedback from the system to the user. It informs users regularly that the system is working properly. If there are no regular vibrations in the suit, the system has a fault. UI components are either selected or sealed to withstand machine washing. Detailed information on the electronics of the system can be found in [S3].

Textile electrodes were utilized in the suit instead of commercial gel-paste electrodes for two reasons. Firstly, textile electrodes were thought to be more clothing-like and, therefore, better solutions for clothing applications. Secondly, it was first found that commercial electrodes were not suitable for mobile measurements since they were originally intended for stationary use [S3]. To compare these electrodes, functionality tests were made using commercial electrodes as well as textile electrodes. Those tests showed that both electrodes are suitable for bioimpedance measurements for mobile users if the commercial electrodes can be securely fastened to the surface of skin [S4]. However, commercial electrodes are disposable and more difficult to use than textile ones.

To evaluate the functionality of the system, volunteers tested the suit in three different types of exercises: walking, fitness biking, and running. Furthermore, reliability of the system has also been evaluated in reference measurements performed in a sauna. Test sessions were intended for estimating long-term exercise so that changes in water balance in the body could be monitored.

Walking tests showed that TBW values decrease during long walking sessions. Tests were also made in which testers drank water while walking. In some of these tests the decrease in TBW stopped but in other tests the TBW decreased further. However, the decrease in the TBW became slower when drinking. In more physically demanding sports (running and fitness biking) the test results were not as obvious as in walking. TBW values decreased only little if at all, while in the running tests TBW values seemed to increase. Cornish et al. have observed that temperature and sweating affect bioimpedance values and this could also explain our results [28]. Therefore, we performed a few tests in a sauna to measure temperature under the measurement electrode. It was concluded that the increase in temperature could explain the behavior of measurements.

Nine individuals each tested the suit several times. Wearing comfort was found to be good and the additional electronics caused no discomfort. The UI was found to be very easy to use and, in general, the feedback system was found to be very satisfactory. However, during exercise, the three minute intervals between vibrations were sometimes considered to be too long. Systematic usability tests for the suit were not performed since it was more important to evaluate the functionality of the concept itself.

Overall, physiological measurement implementation in a clothing platform was found to be challenging. The textile electrodes proved to be reliable and suitable for use in clothing. However, electrodes need to be attached firmly to the surface of skin to ensure good contact. While moving, bad contacts produce movement artifacts and this complicates the recognition of real signals. Textile electrodes can be utilized several times, though repeated usage may eventually impair the electrical conductivity of electrodes. This research demonstrated that textile electrodes, which are connected to the suit with snap fasteners and adjusted to be suitable in length by Velcro tape, were easy to use. An electrode utilized in the bioimpedance prototype is illustrated in Figure 25. Electrodes were also found to be comfortable to wear. However, more tests are needed to evaluate different types of electrode so that users can compare their experiences using them.

The bioimpedance measurement system was generally found to be useful to monitor trend changes in TBW, though absolute TBW values cannot be estimated reliably. There are numerous other factors affecting bioimpedance of the body and, in general,

Figure 25. Textile electrode utilized in bioimpedance measurements [P6].

bioimpedance measurements are prone to change according to different body postures. Therefore, there is a clear need to perform segmental bioimpedance measurements to provide information on impedance changes in the legs, arms, and torso before the overall reliability of the system can be evaluated. In this measurement platform, the user needs to connect the jacket and trousers together with additional fasteners to provide galvanic contacts for the measurement. The electrodes also need to be connected to the suit separately in order to achieve good contacts between them and the electronics. This is impractical since it impedes the typical usage of clothes. The appearance of the suit is like that of ordinary clothing and there are no additional components protruding from the clothing. The UI switch and push buttons are marked on the suit in an unobtrusive way. Along with user opinions, we can conclude that the integration was successful.

4.1.5 CityGuide Usability Evaluation

The increasing number of gadget-type applications means that they must also be user friendly. CityGuide is a mobile mapping application providing its users with information about different places as well as information on their location on an electronic map [P7]. The PPM vest was implemented utilizing distributed architecture of the system and its integration into clothing. CityGuide, on the other hand, is a single appliance, which can be carried in pockets or bags while not in use. The application is intended to be utilized in mobile phones or PDAs.

Acceptance of the CityGuide application is tested with a pilot study and conventional usability tests. The platform used in the tests for the application is the Nokia 9210 communicator [214]. The application introduced the major sights and services of Tampere. Users of the application were able to search the categorized services or sights by using Search Target or Address functions. The services found appeared on the map as a colored spot. In these tests it was not possible to employ user positioning. Though the necessary software options for this were available, no commercial hardware

Figure 26. Start window of CityGuide application [P7].

Table 2. Test assignments for usability evaluations.

	Test assignments
1.	Start the CityGuide application
2.	Menu usage:
	a) Set all OTHER targets viewable
	b) Test functions: move to the left and to the right
	c) Search infromation from the Pyynikki observation tower by using the Info tool
3.	Search Sokos Hotel Ilves
4.	Search Itsenäisyydenkatu 5
5.	Search the web site address of the Hakametsä
	indoor ice-skating rink
6.	Test functions: bring closer and farther away
7.	Close the application

accessories existed at the time. It was also possible to get additional information on some of the targets, such as opening hours and the addresses of web sites. The start window of CityGuide application is shown in Figure 26. The four buttons on the right of the display are used as shortcut keys and their functionality depends on the mode of the application. The application can also be utilized with the general menu key of the device.

The application was tested in a pilot study for a month by 26 tourism workers. Each worker was sent an email questionnaire to chart their opinions. Of the 26, 18 responded to the questions. A conventional usability study can be divided to three parts. Firstly, the test persons complete a questionnaire dealing with their background information. Next, they perform prearranged test assignments in the laboratory and finally, they complete a questionnaire concerning their own opinions about the application. The test group had different backgrounds to the pilot group and this provided two different perspectives for evaluating the application.

The test assignments for the ten persons participating in tests are presented in Table 2. The assignments were intended to test the basic usage of the system. In addition, it was noted in the preliminary tests that menu usage was difficult and therefore it was tested twice to ascertain if it can be learned during testing. On the basis of our own tests, it was estimated that test performance should take about thirty minutes.

Analysis of the tests started with lettering the video that was recorded during performance of the tests. Then problems and comments from the video were collected and categorized. Next, questionnaires completed by ten test persons were analyzed before the pilot group. Finally, the results obtained from these two groups were compared.

From the performance times calculated for each test assignments, it was observed that every test person encountered problems with one or more of the test assignments. However, the basic functioning was found to be straightforward. By taking the phone in the hand and starting the software, it was easy to search for targets or addresses. This application has both hardware and software parts, which affect the usability of the system. These, however, were not separated in this research since, for actual users, this information is unnecessary. Another reason for this was that the system was not implemented in our institute and so giving reasons for the problems would have involved more guesswork than information.

In this particular application there was a significant advantage if the phone was already familiar to the user. In the second and fifth test assignments, in which users' need to use layers indicating different services or sights in Tampere, users select the menu button of the device. In earlier versions of the phone there was no such button and for new users its function was unclear. It appears, then, that the UI function is not very intuitive since without instructions it is difficult to employ the functions apart from zooming and basic searching. Therefore, the choice of test method could have been different. In this kind of application it is natural to first try out the system and learn to use it. However, due to the schedule and the amount of available hardware and software other approaches were not possible.

Compatibility problems with the hardware and software tools made the application very slow to start up. Some of the test persons found this irritating and with resultant negative feelings throughout the testing procedure. Therefore, a better solution might have been to start the application for the users, since there were no errors found in that assignment and starting the application was found to be intuitive. In addition, it was not possible to use the phone for any other purpose when using the application. These were not fatal problems but they significantly complicated the usage. Questionnaires given to test persons revealed similar notices that were observed during the testing. Users also found the lack of feedback confusing. When the application was slow, the users were inclined to press the buttons several times before anything happened.

In the pilot study group, users tested the application by themselves. This is actually an idea that was thought to work well in the test group. However, the pilot group were from very different backgrounds and not necessarily familiar with new technology. In this case a short learning session would have been beneficial but this pilot group study was not actually administered by testers. Therefore, we considered any feedback from the group to be a bonus. The fatal problem in the pilot group was crashing of the application, which necessitated removal of the battery to reboot the system. Some members of the pilot study found this so tiresome that they gave up using the application altogether.

Despite the drawbacks of the system, both groups also noted advantages. The test group thought that the concept of the application was very good. The pilot group had more reservations and this was attributed to their backgrounds. It may have been that the test group thought that the application represented new things to do and experience. The pilot group regarded the application's usefulness and usability in actual situations and compared its use to the map usage. However, with the added positioning option together with a traditional map, this application was considered useful by both tests groups. It was also found to be positive for the image of Tampere. The system was easy to learn, provided the user read the instructions. It was not possible to estimate the memorability of the system. Efficiency proved to be rather poor because of the slow operation of the system in certain functions. In error situations, the system provided no guidance for the user, though this was only observed in the pilot study group.

4.2 Enabling Technologies

Technologies needed in smart clothing implementations are actually technologies that can make the applications more clothing-like. It will, therefore, be worth considering ECF usage in more detail. Generally, ECF materials in clothing can be utilized for data and power transfer as well as for UI devices and sensing elements [P9, 157, 222].

4.2.1 ECF Usage in Clothing for Cable Replacements

For data and power transfer, ECF materials are commonly utilized as yarns so that one yarn can replace a core of an ordinary cable. Bare ECF yarns are also electrically conductive on their surface, which may limit their usage in wire channels in clothing to avoid unwanted short circuits. On the other hand, different types of sealants on the surfaces of yarns can make the yarn more inflexible. Therefore, the benefit of ECF utilization may be lost. Typically ECF yarns are formed utilizing thin metal wires such as stainless steel or by plating a suitable core material with electrically conductive materials [15]. Examples of the latter are metal clad aramid fiber yarns, silver coated polyester or polyamide yarns, and polyaniline coated polyethylene terephtalate fiber yarns [39, 46, 89]. Metal based yarns can be soldered when utilized but for plastic-based fibers electrically conductive adhesives need to be utilized.

Marculescu et al. have investigated the characteristics of copper coated polyester yarns for signal transmission [123]. These yarns were coated with polyesterimide for insulation. They found that yarns can be utilized reliably for digital data transmission at 100 MHz and it is possible to optimize fabrics and signal line configurations. Therefore, ECF materials can be utilized for signal transmission lines in addition to power transfer and EMI shielding.

In the present research metal clad aramid fiber yarns have been used to replace plastic insulated cables for power and data transfer in internal communication. They have been utilized particularly in lightweight underclothes, in which wearing comfort may be radically impaired by utilizing thick and inflexible cables. In the sensor shirt, ECF is utilized to connect one-wire temperature sensors together [P4]. The most challenging tasks have been the implementation of reliable joints between the fiber yarn and temperature sensors as well as between the yarn and the PWB [P4]. The same problem was also encountered in [123].

In the configurations here, ECF yarns have been utilized as additions to ordinary textile materials. However, a more sophisticated solution is to weave the ECF yarn directly into fabric material [123, 157]. In this way, buses for data and power transfer can be integrated comfortably into textile structures. The electronics components can then be attached at suitable locations utilizing press fasteners or other types of fastener. For designers these integrated solutions are more demanding than ECF utilization in separate yarns. This is because it must be known at the outset of the weaving process where the wires should be in the textile material as well as other information such as how many wires run in parallel. In addition, the pins of the components are in a certain order and it is important to know where the data wires needed in the connection are joined. To overcome this problem, a configurable pin arrangement for components can be utilized [111]. In this prototype design, the signal pins of components can be configured after placement in the clothing. Therefore, it can be determined which pins in different components are connected to each other and functionality can be adjusted accordingly.

4.2.2 Connections with ECF

A problem with ECF material connections was identified at interfaces between the yarn and electronics. As a result, electrically conductive adhesives were utilized to make the actual connection point softer. When connecting ECF yarns to temperature sensors employed in heating prototype 2, heat-shrinkable tubes were utilized between component pins to avoid short circuits [P4]. It was later noticed that the interfaces between the yarn and hard materials such as PWBs or heat-shrinkable tubes also broke easily. Therefore, ways of forming reliable connections need to be developed before ECF can be utilized as a cable replacement.

Research utilizing silver clad aramid fiber yarns and stainless steel yarns was carried out to determine if reliable connections can be made utilizing proper materials and connection mechanisms [P9]. Solder and electrically conductive adhesives were used as joining materials. To test the reliability of these connections, we carried out accelerated environmental reliability tests and a tensile strength test to measure the strength over the connection. Accelerated environmental tests are used to speed up the functions of damage mechanisms in connections. The most likely environmental hazards to damage connections are temperature and humidity [228]. Both of these parameters were included in our testing. There were ten examples of the same connection types in a sample board to ensure reliability of the results. The sample board is shown in Figure 27. The samples are placed in a climate chamber for testing and the voltage over each joint is measured continuously. An increase in the voltage indicates higher resistance over the joint and eventually breakage.

The first test carried out was the humidity and temperature cycling test according to standard MIL-STD-202F. On completion of this test all the connections were functional. However, voltages over the stainless steel yarn connections changed more clearly according to temperature than voltages over the silver clad aramid fiber joints and voltages over adhesive joints were greater than the voltages over solder joints for

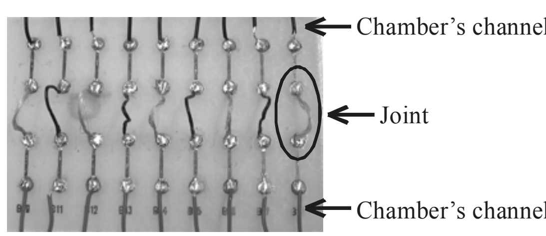

Figure 27. Joint sample board [P9].

Table 3. Tensile strength test results.

Joining materials	Avg/ N	Sd
Through hole, SnPb solder	43,34	3,26
Through hole, SnPb solder, silicone	40,83	6,09
Surface mount, SnPb solder	32,19	13,03
Surface mount, SnPb solder, silicone	41,58	10,64
Through hole, thicker FR4	44,49	6,04
Through hole, smaller drill hole	41,74	5,21
Through hole, Loctite adhesive	56,34	1,4
Through hole, EMS adhesive	42,74	4,87
FR4 horizontally, through hole, SnPb solder	30,46	7,78

both types of yarns.

The second test was a thermal shock test according to Jedec-104A standard. In this test the rate of temperature change was greater than in the first test and therefore was considered to be more demanding on the joints. Though all the connections were still functional at the end of these tests, the silver clad aramid fiber yarn connections fared much better than the stainless steel yarn joints. This is a consequence of the lack of experience making the connections with the stainless steel yarn and its greater resistivity. As a result silver clad aramid fiber yarn connections are thought to be more reliable for long-term usage. In general, however, the solder joints were better than the adhesive joints. This was expected since the glass transition temperatures of the materials were below or the same as the highest temperature in the tests. They do not, therefore, withstand such high temperatures and adhesives start to detach from the connection spot.

Tensile strength tests determine the mechanical strain durability of joints. The stainless steel yarns were unsuitable for testing and so only silver clad fiber yarns were utilized. Ten samples having the same joining materials were tested and the results are shown in Table 3. Both surface-mount and through-hole connections, as well as solder and two types of adhesive were tested. In the table the averages and standard deviations of breaking strengths have been calculated. The best breaking strength was achieved using Loctite adhesive.

The results show that the solder joints survive better in the accelerated environmental tests whereas the adhesive joints have more strength. Since all the connections were still functional even after the second environment tests, it was not possible to identify the actual breaking mechanisms of ECF yarn joints. However, these results show it is possible to achieve reliable connections. As is often the case in wearable electronics research, conventional methods are not suitable. This is mostly due to the application environment, which is more demanding than that for typical electronics devices. This was also the case with these reliability tests and therefore new test methods need to be developed. In these tests, there is also a need to investigate other properties such as ECF yarn movement and abrasion against other hard materials.

4.2.3 Connection Mechanisms

Various connection mechanisms are associated with wired communication methods. In clothing, these mechanisms need to have clothing-like properties. Therefore, one solution is to utilize suspenders, press fasteners, and buttons as connectors to connect different pieces of clothing galvanically, sensors to clothing, and small electronics components to clothing platform [P6, P10]. Another approach is to utilize suspenders as a harness for the clothing accessories, namely electronics modules [55]. Press fasteners having needle fracture stringers are easy to connect and disconnect to the power bus provided by the suspender.

In smart clothing applications connectors are problematic due to their large size and the fact that connectors impair usage of the clothing. Since clothing has its own possibilities for connectors, the principle of combining a component encasing and a connector was investigated and developed [S8, P10]. The basic idea is to utilize a button or button-like shape as a molded encasing over an electronics component or an assembly. This button structure is then sewn onto the clothing utilizing ECF and a traditional needle. When electrically conductive areas on the clothing and ECF yarns come into contact with each other, a galvanic connection is formed between the component and the clothing. The structure of the button component encasing is illustrated in Figure 28. First, the component is soldered onto electrically conductive sleeves and then the encasing is molded over it. This implementation has been verified with a one-wire temperature sensor inside the component encasing. The identification number of this sensor was requested from the button component, which verified the connection between the sensor and ECF in the clothing. However, the long-term durability and reliability of the concept need further study.

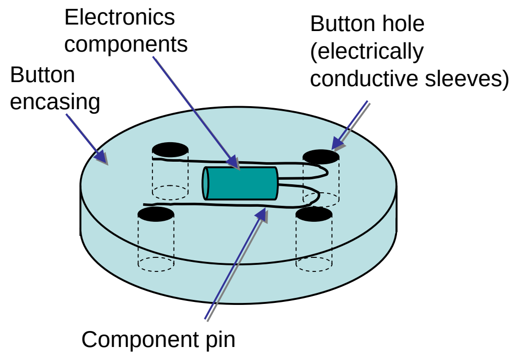

Figure 28. Button component encasing concept [P10].

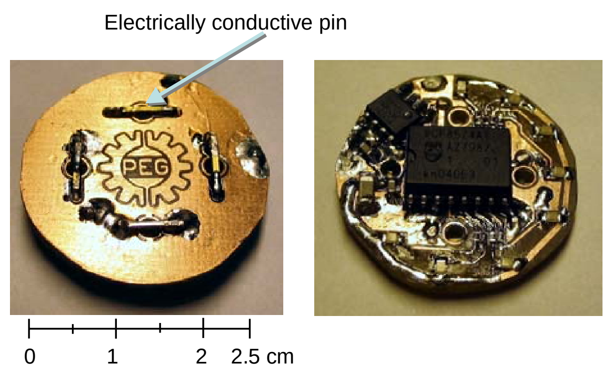

Figure 29. Electronics circuit assembly for button component encasing [P10].

A more sophisticated solution is to design an electronics circuit inside the button encasing as shown in Figure 29. In this structure ECF yarn is sewn over electrically conductive pins, also shown in Figure 29. The advantage here is that there are more connections available to the outside world. In the typical button only two connections exist, whereas in this solution there are four separate connections. The reliability of this system still needs to be demonstrated because of problems encountered when ECF yarns are in contact with hard objects.

The same idea is also examined in [104]. Linz et al. utilize flexible PWB as a platform for electronics assembly. Drilled holes for the connections are located at the edges of the boards. Wires are embroidered into the textiles and the assembly board is sewn into a suitable location. Finally, protection encasing is molded over the assembly. Their results show that the technique is functional. Multiple sewing with ECF yarns improves the connection and reduces contact resistance. These results are promising and indicate that research for these connection techniques is on the right track.

4.2.4 ECF Usage in Sensing Elements

ECF yarns are utilized for electrodes in various clothing applications [209, 222, 223]. Typical commercial electrodes utilized, such as those for ECG measurements, are disposable, need conductive material between skin and the electrode, and not intended for mobile use. The advantages of textile electrodes are that they can be utilized several times, they fit naturally into the clothing structure, they do not need additional conductors between skin and electrodes, and they can be integrated directly into the clothes. This makes them easier to utilize than commercial gel-paste electrodes.

Wearable electronics users are mostly unfamiliar with measurement systems. Increasingly, electrodes will be applied to a wide variety of situations and also in daily life to continuously measure human physiological data signals. It is therefore important that electrodes are easy to use, robust, reliable, comfortable, and integrate unobtrusively into the clothing structure [90].

These kinds of textile electrodes are prone to motion artifacts which result when electrodes move with respect to each other. We, therefore, used elastic bands as bases for electrodes [S4]. The bands can be adjusted according to different body size, allowing the electrodes to fit tightly on the skin, thereby, minimizing motion artifacts. Electrodes are also integrated directly into clothing [209]. In this case the clothes need to be tight-fitting to allow skin contact.

5 Summary of Publications

This Thesis consists of *eleven* publications based on the author's work between 1998 and 2005. The work concentrates on wearable electronics design, especially the evaluation of smart clothing prototypes in several applications. Since the clothes are in close proximity to the user, the work also considers usability and user acceptance issues. In this chapter, there is a summary of each publication and an explanation of the author's contribution. Publications [P1] – [P11] have not been used elsewhere as a part of a doctoral thesis.

The publications can be divided into two categories. First, publications [P1] – [P7] deal with wearable electronics prototypes, whose applicability with the developed applications is evaluated. Second, publications [P8] – [P11] focus on technologies needed for wearable electronics and for their integration into clothing. Since smart clothing design often creates the need for intelligence distribution to several locations in clothing, these publications deal with communication-related technologies.

Publication [P1] describes the complete smart clothing prototype implementation for arctic environment applications. According to the authors' knowledge, this was the first complete large-scale smart clothing prototype to be designed and implemented. The design procedure begins with the specification of the target user group and its needs. Together with technological constraints, this creates the framework that has to be solved. The developed and applied technologies are integrated to form clothing that has augmented functionality.

The author designed and implemented the system together with the project group. This publication deals with the electronics design and implementation, which was carried out by the author and Mikko Tasanen, MSc. The author designed the sensor and measurement system and participated in communication, positioning, and power source design and implementation. Jussi Impiö, MA designed the user interface concept and Mr. Mikko Malmivaara designed the clothing. Tapio Karinsalo, MSc, implemented the software for the system. Akseli Reho, MSc was project leader. The author wrote the publication together with Mikko Malmivaara, Mikko Tasanen, and Professor Jukka Vanhala.

Publication [P2] presents the sensor system and the decision logic implementation of the arctic environment smart clothing prototype. The author designed the sensor system for the application. Akseli Reho led the project and Tapio Karinsalo implemented the software for the measurement system. Mikko Tasanen designed the electronics for the user interface and central processing unit of the system. The author wrote the publication together with Professor Jukka Vanhala.

Publication [P3] introduces the electrically heated clothing prototype. The main goal of the design was to improve the functionality of ordinary clothing by an additional heating option. Architecture for the prototype is described in terms of its functionality and its suitability for the intended purposes. User tests were performed with this prototype.

The author designed the concept for the heating prototype and developed the system together with the project group. The author designed and carried out the tests, and analyzed the test results of the user tests together with Outi Ryynänen, MSc. Kari Kukkonen, MSc implemented the hardware for the prototype and Timo Vuorela, MSc made software for the user interface. Arto Siili, MSc took part into the design of the system. The author supervised the project design. The author wrote the publication and Outi Ryynänen wrote the section on heat loss and heating power. Professor Jukka Vanhala reviewed the writing style.

Publication [P4] is the continuation of publication [P3]. Here a new prototype is designed according to the test results and user opinions of the first electrically heated clothing prototype. The author designed the new system with the assistance of the project group. Timo Vuorela implemented the sensor shirt for this second prototype. Kari Kukkonen, Arto Siili, and Outi Ryynänen made valuable suggestions for the system design. The author supervised the project design. The author wrote the publication and Professor Jukka Vanhala reviewed the writing style of the text.

Publication [P5], describes a wearable clothing prototype for determining the user’s location. The author designed the prototype concept together with the project group. The author evaluated the prototype’s functionality and tested the applicability of the user-centered design methods for wearable electronics design. Mr. Tero Alho implemented the system and carried out the preliminary tests for the functionality evaluation. Kari Kukkonen took part in the concept design. Timo Vuorela specified the communication between the user interface and the system. Prof. Jukka Vanhala provided advice for the wearability design of the system. The author supervised the project design and wrote the publication.

In *publication [P6]*, a wearable bioimpedance measurement system for total body water estimation is presented. The author designed the prototype concept together with the project group. The author also designed the testing procedure and analyzed the results together with Timo Vuorela. The author supervised the project design. The author wrote the publication and Timo Vuorela assisted with the hardware implementation part. Professor Jukka Vanhala reviewed the writing style of the manuscript.

Publication [P7] evaluates the functionality of the wearable information manager application. This application represents a more familiar type of wearable system, since the platform is a mobile phone. The author designed the usability evaluation tests and analyzed the results. Erja Jokinen, Lic.Tech. took part in the evaluation of the results and performed the tests together with the author. Jari Reini, MSc gave technical details on the application and valuable advice on the text. Professor Jukka Vanhala supervised the project. The author wrote the publication.

Publication [P8] evaluates suitable communication technologies for wearable applications. The publication introduces a smart clothing concept model, which can be utilized as one of the guidelines when placing components in clothes. Furthermore, the publication presents the needs for communication and a communication model that can be utilized in selecting data transfer methods for smart clothes. Potential technologies are proposed and the communication utilized in smart clothing prototypes described in publications [P1-P6] is evaluated according to the proposed models. The author designed the clothing model and the communication model for smart clothing usage and evaluated the performance of the prototypes. Dr. Marko Hännikäinen provided technical information on wireless communication and reviewed the writing style of the text. The author wrote the publication.

Publication [P9] evaluates the usability of electrically conductive fibers in smart clothing applications. Three types of electrically conductive fibers are introduced and their applicability to cable replacement and as sensor elements is proposed. The publication concentrates on connection mechanism reliability. The author wrote the publication and evaluated the applicability of electrically conductive fibers to smart clothing applications. Tiina Järvinen, MSc implemented the reliability tests and performed the preliminary analysis of the results. Timo Vuorela reviewed the writing style of the manuscript. Mrs. Katja Vähäkuopus partially implemented the sensors described in the publication. The author supervised the work of Tiina Järvinen. Professor Jukka Vanhala reviewed the writing style.

Publication [P10] introduces a novel system for electronics component encasings for wearable electronics systems in clothing and for galvanic connections between the electronics and clothing. The author designed the concept together with Mr. Jussi Mikkonen. A national patent has also been granted for the system in Finland. The author wrote the publication. Professor Jukka Vanhala reviewed the writing style.

Publication [P11] studies Bluetooth antenna design on flexible substrates. The proposed use is to implement these clothing-like antennas in clothing. Dr. Pekka Salonen designed and implemented the tested antenna and wrote the most of the manuscript. The author wrote the sections dealing with smart clothing and the proposed application. The author also performed the tests together with Pekka Salonen and participated in the design of the antenna placement on the test platform.

6 Conclusions

Smart clothing prototypes and wearable electronics systems are introduced with the focus on their design, requirements, and user acceptance. Eleven publications in this thesis describe the prototypes and their performance as well as data transfer methods and ECF usage.

First, the most important concepts utilized in the wearable electronics field are presented. The definition of smart clothing of this thesis was specified during the Cyberia project. Furthermore, the survey of wearable applications examined the kind of applications that can be implemented utilizing clothing or its accessory-based platforms. Second, smart clothing design process is introduced with the emphasis strongly on user needs. Smart clothing design requirements according to usage environment, electronics, and clothing are discussed as well as issues related to usability and acceptance of the systems. In smart clothing design, the user plays as important role as technological aspects and, therefore, clothing-like elements need to be utilized as often as possible to achieve wearing comfort. The smart clothing concept model introduced is a practical tool for use in designing the placements of components between the different clothing layers. Potential subcomponents of clothing applications were also examined. This research showed clearly that smart clothing systems need different subcomponents to those used in traditional wearable computer applications.

The main outcome of the Cyberia project was the implemented and fully functional smart clothing prototype. According to the author's knowledge, this was the first of its kind in the world. The clothing platform and users' needs were also considered in this project. Accordingly, the project also presented information on the smart clothing implementation phases, namely the design flow and the importance of interdisciplinary. The functional prototype with the appearance of ordinary clothing, demonstrated that these systems can indeed be designed and implemented. The new technologies utilized in the design were application-specific solutions to a variety of problems. These included a specific UI, ECF usage in sensing elements, component concealment in the clothing structure, non-electronic functions, and electronics designed to be small, lightweight, and robust enough to permit their use even in extreme winter conditions.

Those involved in the project believe this is a field of research with major importance for the future. However, the Cyberia concept was on such a large scale that the cost of the commercial product would have been too high for consumers. Therefore, applications are needed that have fewer functions and are simple to implement.

To improve the basic functionality of clothing, two electrically heated smart clothing prototypes are designed and implemented. In the prototypes, the heated fabric is utilized as the heat source. This is a different approach to the ones typically adopted. More commonly electric heating is implemented by means of resistive wires or other heating methods such as chemical heating. The implementation of the system was the main goal for studying the functionality of the concept and its user acceptance.

The design of the electronics was especially demanding since electrical heating needs energy yet consumption has to be minimized in mobile applications. In addition, the implementation of the system was challenging in that it was important to ensure the warmth and comfort of the user. The first prototype demonstrated that the concept could be implemented. User tests were conducted to evaluate functionality in practice, as well as user acceptance of the application. The results reflected some criticism of the appearance of the systems along with unfilled high expectations of users. This led to the design of another prototype. This second prototype has the appearance of ordinary clothing and is also comfortable to wear. The main result of the research was that the system cannot provide as much heat as users would like. In addition, heavy power sources are not easily portable and render their implementation impractical. Test users were fairly critical of the heating power. However, according to temperature measurements, the system is able to prevent a decrease in temperature, thus providing a partial solution to the problem of maintaining the thermal comfort condition.

Positioning is needed in several wearable electronics applications. As a result, its usefulness for integrating the distributed architecture into clothing was also studied. There are commercial solutions available that utilize the same methods in a different package. Since the user plays such an essential role in smart clothing design, the scope for employing user centered design methods was also evaluated. The functional prototype demonstrates that it is possible to construct a positioning system. User centered design methods are somewhat cumbersome for this size of project. However, user evaluations provided important data concerning the design of the system. The specified UI switch was found to be easy to use also in the actual usage conditions. However, additional PDA UI was found to be too difficult to use. Since people are used to carrying gadget-type devices, they prefer systems than can be utilized with different platforms and are not fixed to any particular item of clothing. The electronics proved small enough to be hidden in the outerwear clothing without the need for miniaturization and did not compromise wearing comfort.

User measurements have been one of the most important application areas suggested for these personal applications. For achieving user comfort, clothing-like sensing elements are studied in the bioimpedance measurement system. The electronics for the system are small enough for the prototype, though miniaturization is needed in commercial products. Textile electrodes are functional and can be utilized with the clothing applications. However, their usage still needs additional phases in dressing. The concept of TBW estimation was found only to be indicative and other parallel measurements are needed because the method chosen is difficult to implement when people are moving.

Usability and user acceptance has been found to be especially important for wearable electronics and smart clothing applications. Therefore, user acceptance is investigated to ascertain the advantages gadget-type information devices can provide the user. The results actually showed that it is very important to perform the evaluations under authentic conditions since the environment plays an important role in mobile applications. People unfamiliar with new technological advances are reluctant to accept these new devices as a working partner even if there are only minor problems with usage. These tests showed that it is vital to take usability into consideration. Minor details can undermine the entire experiment for using the system and very negatively affect the choice of using the system again.

Key elements in achieving really usable smart clothing applications were clothing-like solutions. Examples of such technology are ECF for power and data transfer as well as for sensing elements, connection mechanisms suitable for clothing, and data transfer methods chosen according to the communication model. ECF can be utilized for clothing but further research is needed to achieve reliable connections. The results of the tests here indicate that reliable connections are possible but their usage in clothing is so demanding that new test methods are needed to assure their reliability. In sensing elements, ECF provides clothing-like and long-term solutions that are comfortable in use and do not need additional conductors between electrode and skin.

ECF is a natural solution for internal data transfer in an item of clothing because it provides a flexible and reliable data transfer medium. In addition, with button component encasing, the electronics can be concealed inside a traditional clothing element and items of clothing can be connected with buttons. The concept of the button is functional and promising since ordinary textile techniques are suitable for the construction of systems. Wireless data transfer is needed in personal space and external communication. Essential parts of wireless systems include antennas, which are often rigid and cause discomfort to the user. It was proved that flexible PWB materials can be utilized in antenna design and they are found to be suitable for use in clothing. The scope for utilizing ECF materials for antennas needs to be verified in further studies.

The prototypes presented in this thesis demonstrate that the construction of smart clothing systems is feasible and clothing can be used as a platform for electronics. Users' needs should guide the design, and end users should be harnessed for the development processes. For smart clothing to achieve widespread acceptance, appearance will play a crucial role in addition to suitable clothing-like technologies and wearing comfort.

At the start of this work our institute was one of the first research groups to focus on wearability and clothing platform and clothing-like material usage. At present there are several other research institutes in Europe also working on clothing platforms, concentrating particularly on human physiology measurements. The current trend for commercial applications is the adoption of several gadget-type devices. Current research activity and success in the implementation of clothing-like applications strongly suggest that clothing platform usage in wearable applications will determine the future of the field of smart clothing.

References

[1] Abowd, G. D., Dey, A. K., Orr, R., Brotherton, J., "Context-Awareness in Wearable and Ubiquitous Computing", First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 179-180, Cambridge, MA, USA, October 13-14, 1997.

[2] Amft, O., Junker, H., Tröster, G., "Detection of Eating and Drinking Arm Gestures Using Inertial Body-worn Sensors", Ninth IEEE International Symposium on Wearable Computers (ISWC ´05), pp. 160-163, Osaka, Japan, October 18-21, 2005.

[3] Antifakos, S., Schiele, B., "Bridging the Gap Between Virtual and Physical Games Using Wearable Sensors", Sixth IEEE International Symposium on Wearable Computers (ISWC ´02), pp. 139-140, Seattle, WA, USA, October 7-10, 2002.

[4] Arra, S., Heinisuo, S., Vanhala, J., "Acoustic Power Transmission into an Implantable Device", Second International Workshop on Wearable and Implantable Body Sensor Networks (BSN'05), pp. 60-64, London, UK, April 12-13, 2005.

[5] Axisa, F., Dittmar, A., Delhomme, G., "Smart Clothes for the Monitoring in Real Time and Conditions of Physiological, Emotional and Sensorial Reactions of Human", 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS), Vol. 4, pp. 3744-3747, Cancun, Mexico, September 17-21, 2003.

[6] Axisa, F., Gelhin, C., Delhomme, G., Collet, C., Robin, O., Dittmar, A., "Wrist Ambulatory Monitoring System and Smart Glove for Real Time Emotional, Sensorial and Physiological Analysis", 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS), Vol. 3, pp. 2161-2164, San Francisco, CA, USA, September 1-5, 2004.

[7] Ball, J. R., Evans, C. H., Jr., (Eds.), "Safe Passage Astronaut Care for Exploration Missions", National Academy Press, Washington, DC, 291 pages, 2001.

[8] Barbour, N., Schmidt, G., "Inertial Sensor Technology Trends", IEEE Sensors Journal, Vol. 1, No. 4, pp. 332-339, December 2001.

[9] Barfield, W., Mann, S., Baird, K., Gemperle, F., Kasabach, C., Stivoric, J., Bauer, M., Martin, R., Cho, G., "Computational Clothing and Accessories", Barfield, W. & Caudell, T. (Eds.), "Fundamentals of Wearable Computers and Augmented Reality", Lawrence Erlbaum Associates, Mahwah, New Jersey, USA, pp.471-509, 2001.

[10] Barshan, B., Durrant-Whyte, H. F., "An Inertial Navigation System for a Mobile Robot", IEEE/RSJ Intelligent Robots and Systems (IROS´93), pp.2243-2248, Yokohama, Japan, July 26-30, 1993.

[11] Bass, L., Mann, S., Siewiorek, D., Thompson, C., "Issues in Wearable Computing: A CHI 97 Workshop", SIGCHI Bulletin, Vol. 29, No. 4, pp. 34-39, 1997.

[12] Baudhuin, E. S., "Telemaintenance Applications for the Wearable™ PC", 15th Digital Avionics Systems Conference, AIAA/IEEE, pp. 407-413, Atlanta, GA, USA, October 27-31, 1996.

[13] Bauer, M., Heiber, T., Kortuem, G., Segall, Z., "A Collaborative Wearable System with Remote Sensing", Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 10-17, Pittsburgh, PA, USA, October 19-20, 1998.

[14] Baurley, S., "Interactive and Experimental Design in Smart Textile Products and Applications", Personal and Ubiquitous Computing, Springer-Verlag, Vol. 8, No. 3/4, pp. 274-281, July 2004.

[15] Bekaert Group, Belgium, Data sheet of Bekinox VN-Continuous Stainless Steel Filament Yarn.

[16] Beyer, H., Holtzblatt, K., "Contextual Design", Morgan Kaufmann Publishers, San Francisco, CA, USA, 472 pages, 1998.

[17] Billinghurst, M., Starner, T., "Wearable Devices: New Ways to Manage Information", Computer, IEEE, Vol. 32, No. 1, pp. 57-64, January 1999.

[18] Blasko, G., Coriand, F., Feiner, S., "Exploring Interaction with a Simulated Wrist-Worn Projection Display", Ninth IEEE International Symposium on Wearable Computers (ISWC ´05), pp. 2-9, Osaka, Japan, October 18-21, 2005.

[19] Bodine, K., Gemperle, F., "Effects of Functionality on Perceived Comfort of Wearables", Seventh IEEE International Symposium on Wearable Computers (ISWC ´03), pp. 57-60, White Plains, NY, USA, October 21-23, 2003.

[20] Boothroyd, A., "A Wearable Tactile Intonation Display for the Deaf", IEEE Transactions on Acoustics, Speech, and Signal Processing, Vol. 33, No. 1, pp. 111-117, February 1985.

[21] Bosco, C. D., Su, L. P., Girolamo, H., Darty, M., "Maintenance and Repair Support System (MARSS)", Test Technology and Commercialization Conference (AUTOTESTCON'96), IEEE, pp. 336-343, Dayton, OH, USA, September 16-19, 1996.

[22] Burdea, G. C., "Force and Touch Feedback for Virtual Reality", John Wiley & Sons, INC., New York, NY, USA, 1996, 339 pages.

[23] Carr, C. E., Schwartz S. J., Rosenberg I., “A wearable Computer for Support of Astronaut Extravehicular Activity”, Sixth IEEE International Symposium on Wearable Computers, pp. 23-30, Seattle, WA, USA, October 7-10, 2002.

[24] Chamberlain, A., Kalawsky, R., “A Comparative Investigation into Two Pointing Systems for Use with Wearable Computers while Mobile”, Eighth IEEE International Symposium on Wearable Computers (ISWC ´04), pp. 110-117, Arlington, VA, USA, October 31-November 3, 2004.

[25] Cheok, A. D., Teo, S. L., Cao, L., Thang, L. N., “Capture the Flag: A Multiplayer Online Game for Phone Users”, Ninth IEEE International Symposium on Wearable Computers (ISWC ´05), pp. 222-223, Osaka, Japan, October 18-21, 2005.

[26] Cheok, A. D., Wan, F. S., Yang, X., Weihua, W., Huang, L. M., Billinghurst, M.; Kato, H., “Game-City: A Ubiquitous Large Area Multi-Interface Mixed Reality Game Space for Wearable Computers”, Sixth IEEE International Symposium on Wearable Computers (ISWC ´02), pp. 156-157, Seattle, WA, USA, October 7-10, 2002.

[27] Cleveland, G., McNinch, L., “Force XXI Land Warrior: Implementing Spoken Commands for Soldier Wearable Systems”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 183-184, San Francisco, CA, USA, October 18-19, 1999.

[28] Cornish, B. H., Thomas, B. J., Ward, L. C., “Effect of Temperature and Sweating on Bioimpedance Measurements”, Applied Radiation and Isotopes, vol. 49, no. 5-6, pp. 475-476, 1998.

[29] Cottet, D., Grzyb, J., Kirstein, T., Tröster, G., “Electrical Characterization of Textile Transmission lines”, IEEE Transactions on Advanced Packaging, Vol. 26, No. 2, pp. 182-190, May 2003.

[30] Crowell, J., “Battery Arrays, Rechargable Li-ion Battery Power Sources for Marine Applications”, OCEANS 2005, MTS/IEEE, pp. 1-6, Washington, D. C., USA, September 18-23, 2005.

[31] Culver, V. R., “A Hybrid Sign Language Recognition System”, Eighth IEEE International Symposium on Wearable Computers (ISWC ´04), pp. 30-33, Arlington, VA, USA, October 31-November 3, 2004.

[32] Degen, T., Jaeckel, H., Rufer, M., Wyss, S., “SPEEDY: A Fall Detector in a Wrist Watch”, Seventh IEEE International Symposium on Wearable Computers (ISWC ´03), pp. 184-187, White Plains, NY, USA, October 21-23, 2003.

[33] DeVaul, R., Sung, M., Gips, J., Pentland, A., “MIThril 2003: Applications and Architecture”, Seventh IEEE International Symposium on Wearable Computers (ISWC ´03), pp. 4-11, White Plains, NY, USA, October 21-23, 2003.

[34] Dey, A. K., “Understanding and Using Context”, Personal and Ubiquitous Computing, Springer-Verlag, Vol. 5, No. 1, pp. 4-7, February 2001.

[35] Dey, A. K., Salber, D., Abowd, G. D., Futakawa, M., “The Conference Assistant: Combining Context-Awareness with Wearable Computing”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 21-28, San Francisco, CA, USA, October 18-19, 1999.

[36] Dittmar, A., Axisa, F., Delhomme, G., Gehin, C., “New Concepts and Technologies in Home Care and Ambulatory Monitoring”, Lymberis, A. & de Rossi, D. (Eds.), “Wearable eHealth Systems for Personalised Health Management”, IOS Press, Amsterdam, the Netherlands, Vol. 108, pp. pp. 9-35, 2004.

[37] Dooris, M., Moorman, M., Gregory, B., Brown, M., Wright, H., “A Preliminary Comparison of Body-wearable Computers to Modern Audio Equipment in a Microgravity Environment”, SIGCHI bulletin, Vol. 32, No. 1, pp. 57-62, January 2000.

[38] Dooris, M., Moorman, M., Gregory, B., Brown, M., Wright, H., “A Preliminary Comparison of Body-wearable Computers to Modern Audio Equipment in a Microgravity Environment”, SIGCHI bulletin, Vol. 32 no. 1, 2000, pp. 57-62.

[39] DuPont, Richmond, Virginia, USA, Product bulletin of Brand Metal Clad Fibre Type XS0400E-018.

[40] Edmison, J., Jones, M., Nakad, Z., Martin, T., “Using Piezoelectric Materials for Wearable Electronic Textiles”, Sixth IEEE International Symposium on Wearable Computers (ISWC ´02), pp. 41-48, Seattle, WA, USA, October 7-10, 2002.

[41] Ertan, S., Lee, C., Willets, A., Tan, H., Pentland, A., “A Wearable Haptic Navigation Guidance System”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 164-165, Pittsburgh, PA, USA, October 19-20, 1998.

[42] Esposito, C., “Wearable Computers: Field-Test Observations and System Design Guidelines”, Personal Technologies, Springer-Verlag, Vol. 1, No. 2, pp.81-87, June 1997.

[43] Fanger, P.O., “Thermal Comfort Analysis and Applications in Environmental Engineering”, MacGraw-Hill, USA, 244 pages, 1970.

[44] Feiner, S., MacIntyre, B., Höllerer, T., Webster, A., “A Touring Machine: Prototyping 3D Mobile Augmented Reality Systems for Exploring the Urban Environment”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 74-81, Cambridge, MA, USA, October 13-14, 1997.

[45] Fickas, S., Kortuem, G., Segall, Z., “Software Organization for Dynamic and Adaptable Wearable Systems”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 56-63, Cambridge, MA, USA, October 13-14, 1997.

[46] Finnesd Inc., Pirkkala, Finland, Data sheet of Silver Plated Nylon Thread.

[47] Fishkin, K. P., Partridge, K., Chatterjee, S., “Wireless User Interface Components for Personal Area Networks”, IEEE Pervasive Computing, Vol. 1, No. 4, pp. 49-55, October-December 2002.

[48] Forrest, S., Burrows, P., Thompson, M., “The Dawn of Organic Electronics”, IEEE Spectrum, Vol. 37, No. 8, pp. 29-34, August 2000.

[49] Fukumoto, M., Tonomura, Y., “”Body Coupled FingeRing”: Wireless Wearable Keyboard”, Conference on Human Factors in Computing Systems (CHI’97), ACM, pp. 147-154, Atlanta, GA, USA, April 18-23, 1997.

[50] Gallasch, E; Rafolt, D; Moser, M; Hindinger, J; Eder, H; Wiesspeiner, G; Kenner, T: “Instrumentation for Assessment of Tremor, Skin Vibrations, and Cardiovascular Variables in MIR Space Missions”, IEEE Transactions on Biomedical Engineering, Vol. 34, No. 3, p. 328 – 333, 1996.

[51] Gandy, M., Ross, D., Starner, T. E., “Universal Design: Lessons for Wearable Computing”, IEEE Pervasive Computing, Vol. 2, No. 3, pp. 19-23, July-September 2003.

[52] Gemperle, F., Kasabach, C., Stivoric, J., Bauer, M., Martin, R., “Design for Wearability”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 116-122, Pittsburgh, PA, USA, October 19-20, 1998.

[53] Glaros, C., Fotiadis, D. I., Likas, A., Stafylopatis, A., “A Wearable Intelligent System for Monitoring Health Condition and Rehabilitation of Running Athletes”, Fourth Annual IEEE Conference on Information Technology Applications in Biomedicine (ITAB 2003), pp. 276-279, Birmingham, UK, April 24-26, 2003.

[54] Gorlenko, L., Merrick, R., “No Wires Attached: Usability Challenges in the Connected Mobile World”, IBM Systems Journal, Vol. 42, No. 4, pp. 639-651, 2003.

[55] Gorlick, M. M., “Electric Suspenders: A Fabric Power Bus and Data Network for Wearable Digital Devices”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 114-121, San Francisco, CA, USA, October 18-19, 1999.

[56] Gough, P., “Wearable Technology”, Aarts, E. & Marzano, S. (Eds.), “The New Everyday Views on Ambient Intelligence”, pp. 158-163, 010 Publishers, Rotterdam, The Netherlands, 2003.

[57] Grimnes, S., Martinsen, Ø. G., “Bioimpedance & Bioelectricity Basics”, Academic Press, London, UK, 2000.

[58] Grossman, P., “The LifeShirt: A Multi-Function Ambulatory System Monitoring Health, Disease, and Medical Intervention in the Real World”, Lymberis, A. & de Rossi, D. (Eds.), “Wearable eHealth Systems for Personalised Health Management”, IOS Press, Amsterdam, the Netherlands, Vol. 108, pp. 133-141, 2004.

[59] Haniff, D. J., Baber, C., “Wearable Computers for the Fire Service and Police Force: Technological and Human Factors”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 185-186, San Francisco, CA, USA, October 18-19, 1999.

[60] Harris, F. M., Schimpf, M. J., “Zinc-air Rechargeable Batteries for Mobile Power”, Ninth Annual Battery Conference on Applications and Advances, pp. 146-151, Long Beach, CA, USA, January 11-13, 1994.

[61] Hazlett, R. L., “Measurement of User Frustration: A Biologic Approach”, Conference on Human Factors in Computing Systems (CHI ’03), ACM, pp. 734-735, Ft. Lauderdale, FL, USA, April 5-10, 2003.

[62] Healey, J., Logan, B., “Wearable Wellness Monitoring Using ECG and Accelerometer Data”, Ninth IEEE International Symposium on Wearable Computers (ISWC ´05), pp. 220-221, Osaka, Japan, October 18-21, 2005.

[63] Healey, J., Picard, R. W., “StartleCam: A Cybernetic Wearable Camera”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 42-49, Pittsburgh, PA, USA, October 19-20, 1998.

[64] Helal, A. S., Moore, S. E., Ramachandran, B., “Drishti: An Integrated Navigation System for Visually Impaired and Disabled”, Fifth IEEE International Symposium on Wearable Computers (ISWC ´01), pp. 149-156, Zürich, Switzerland, October 8-9, 2001.

[65] Herstad, J., Van Thanh, D., “Wearing Bike Components”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 58-63, San Francisco, CA, USA, October 18-19, 1999.

[66] Hightower, J., Borriello, G., “A Survey and Taxonomy of Location Sensing Systems for Ubiquitous Computing”, Technical Report, UW CSE 01-08-03, University of Washington, Department of Computer Science and Engineering, Seattle, WA, August 2001, URL=” http://seattle.intel-research.net/people/jhightower/pubs.html ”, 25.9.2006.

[67] Home page of Parvus Corporation, Salt Lake City, UT, USA, URL = “ http://www.parvus.com/”, 29.7.2006.

[68] Home page of Textiles Intelligence Company, Wilmslow, UK, URL = “ http://www.textilesintelligence.com/ “, 22.6.2006

[69] Home page Polar Electro, Inc., Kempele, Finland, URL= “ http://www.polar.fi/ “, 29.7.2006.

[70] Home page Suunto, Inc., Vantaa, Finland, URL= “ http://www.suunto.com/ “, 29.7.2006.

[71] Homepage of Scottevest, URL = “ http://www.scottevest.com/ “, 29.7.2006.

[72] Howard, B., Howard, S., “Lightglove: Wrist-worn Virtual Typing and Pointing”, Fifth IEEE International Symposium on Wearable Computers (ISWC ´01), pp. 172-173, Zürich, Switzerland, October 8-9, 2001.

[73] Hum, A. P. J., “Fabric Area Network – A New Wireless Communications Infrastructure to Enable Ubiquitous Networking and Sensing on Intelligent Clothing”, Computer Networks, Elsevier, Vol. 35, No. 4, pp. 391-399, March 2001.

[74] Häkkinen, T., Vanhala, J., “Infrared Active Tag Equipment for Identification and Indoor Positioning Applications”, Second International Conference on Machine Automation (ICMA 2000), pp. 383-388, Osaka, Japan, September 27-29, 2000.

[75] Häkkinen, T., Viskari, M., Vanhala, J., ”HereUR! – A Personal Location-aware Information Manager for Wearable Computers”, Conference on Human Computer Interaction: Interfacing Reality in the New Millennium (OZCHI 2000), pp.22-23, Sydney, Australia, December 4-8, 2000.

[76] Höllerer, T., Feiner, S., Pavlik, J., “Situated Documentaries: Embedding Multimedia Presentations in the Real World”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 79-86, San Francisco, CA, USA, October 18-19, 1999.

[77] IEEE Computer Society, “Digest of Papers of the First IEEE International Symposium on Wearable Computers (ISWC ´97)”, Cambridge, MA, USA, October 13-14, 185 pages, 1997.

[78] ISO 9886, “Evaluation of Thermal Strain by Physiological Measurements”, 1992.

[79] Jebara, T., Eyster, C., Weaver, J., Starner, T., Pentland, A., “Stochasticks: Augmenting the Billiards Experience with Probabilistic Vision and Wearable Computers”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 138-145, Cambridge, MA, USA, October 13-14, 1997.

[80] Jung, S., Lauterbach, C., Strasser, M., Weber, W., “Enabling Technologies for Disappearing Electronics in Smart Textiles”, IEEE International Solid-State Circuits Conference (ISSCC 2003), Vol. 1, pp. 386-387, San Francisco, CA, USA, February 9-13, 2003.

[81] Kaasinen, E., “User Needs for Location-Aware Mobile Services”, Personal and Ubiquitous Computing, Springer-Verlag, Vol. 7, No. 1, pp. 70-79, May 2003.

[82] Kaefer, G., Prochart, G., Weiss, R., “Wearable Alertness Monitoring for Industrial Applications”, Seventh IEEE International Symposium on Wearable Computers (ISWC ´03), pp. 254-255, White Plains, NY, USA, October 21-23, 2003.

[83] Kaefer, G.; Prochart, G.; Weiss, R.; **“**VECAS – A Virtually Enhanced Communication Assistance System for Application of Wearable Computing in Motor Racing”, Sixth IEEE International Symposium on Wearable Computers (ISWC ´02), pp. 160-161, Seattle, WA, USA, October 7-10, 2002.

[84] Kalawsky, R. S., “The Science of Virtual Reality and Virtual Environments”, Addison-Wesley, Cambridge, UK, 405 pages, 1993.

[85] Kasai, I., Tanijiri, Y., Endo, T., Ueda, H., “A Forgettable Near Eye Display”, Fourth IEEE International Symposium on Wearable Computers (ISWC ´00), pp. 115-118, Atlanta, GA, USA, October 16-17, 2000.

[86] Knight, J. F., Baber, C., Schwirtz, A., Bristow, H. W., “The Comfort Assessment of Wearable Computers”, Sixth IEEE International Symposium on Wearable Computers (ISWC ´02), pp. 65-72, Seattle, WA, USA, October 7-10, 2002.

[87] Knight, J. F., Schwirtz, A., Psomadelis, F., Baber, C., Bristow, H. W., Arvanitis, T. N., “The Design of the SensVest”, Personal and Ubiquitous Computing, Springer-Verlag, Vol. 9, No. 1, pp. 6-19, January 2005.

[88] Koncar, V., Deflin, E., Weill, A., “Communication Apparel and Optical Fibre Fabric Display”, Tao, X. (Ed.), “Wearable Electronics and Photonics”, pp.155-176, Woodhead Publishing Limited, Cambridge, England, 2005.

[89] Koncar, V., Kim, B., Nebor, E. B., Joppin, X., “FICC (Floatable Intelligent and Communicative Clothing) Project – Conductive Fibers Development”, Eighth IEEE International Symposium on Wearable Computers (ISWC ´04), pp. 36-39, Arlington, VA, USA, October 31-November 3, 2004.

[90] Korhonen, I., Pärkkä, J., Van Gils, M., “Health Monitoring in the Home of the Future”, IEEE Engineering in Medicine and Biology Magazine, Vol. 22, No. 3, pp. 66-73, May-June 2003.

[91] Kotanen, A., Hännikäinen, M., Leppäkoski, H., Hämäläinen, T. D., **“**Positioning with IEEE 802.11b Wireless LAN**”**, IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC2003), pp. 2218-2222, Beijing, China, September 7-10, 2003.

[92] Kuwata, Y., Ishikawa, Y., Ohtani, H., “An Architecture for Command and Control in Disaster Response Systems”, 26th Annual Conference of the IEEE Industrial Electronics Society (IECON 2000), Vol. 1, pp. 120-125, Nagoya, Japan, October 22-28, 2000.

[93] Kymissis, J., Kendall, C., Paradiso, J., Gershenfeld, N., “Parasitic Power Harvesting in Shoes”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 132-139, Pittsburgh, PA, USA, October 19-20, 1998.

[94] Kärki, S., Lekkala, J., Honkala, M., Peltonen, P., Mattila, H., Cluitmans, L., Mattila, J., Väätänen, A., Cömert, A., Hyttinen, J., Hännikäinen, J., Tieranta, T., Vanhala, J., Piipponen, K., Sepponen, R., ”Smart Clothing for Firefighters”, International Scientific Conference of Intelligent Ambience and Well-Being (Ambience 05), pp. 221-229, Tampere, Finland, September 19-20, 2005.

[95] LaRowe, R., Elliot, C., “Computer Networks for Wearable Computing”, Barfield, W. & Caudell, T. (eds.), “Fundamentals of Wearable Computers and Augmented Reality”, Lawrence Erlbaum Associates, Mahwah, New Jersey, USA, pp. 715-745, 2001

[96] Lauter, J., “MyHeart: Fighting Cardiovascular Disease by Preventive Lifestyle and Early Diagnosis”, Lymberis, A. & de Rossi, D. (Eds.), “Wearable eHealth Systems for Personalised Health Management”, IOS Press, Amsterdam, the Netherlands, Vol. 108, pp. 36-42, 2004.

[97] Lee, K., Kwon, D.-S., “Wearable Master Device Using Optical Fiber Curvature Sensors for the Disabled”, International Conference on Robotics & Automation (2001 ICRA), IEEE, Vol. 1, pp. 892-896, Seoul, Korea, May 21-26, 2001.

[98] Lehikoinen, J., “Virtual Pockets”, Fourth IEEE International Symposium on Wearable Computers (ISWC ´00), pp. 165-166, Atlanta, GA, USA, October 16-17, 2000.

[99] Lehikoinen, J., ”Wearable Computer as a Personal Navigation Assistant”, Academic Dissertation, University of Tampere, 2002.

[100] Lehikoinen, J., Holopainen, J., Salmimaa, M., Aldrovandi, A., ”MEX: A Distributed Software Architecture for Wearable Computers”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 52-57, San Francisco, CA, USA, October 18-19, 1999.

[101] Leonhardi, A., Kubach, U., Rothermel, K., Fritz, A., “Virtual Information Towers – A Metaphor for Intuitive, Location-Aware Information Access in a Mobile Environment”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 15-20, San Francisco, CA, USA, October 18-19, 1999.

[102] Lind, E. J., Eisler, R., Jayaraman, S., Park, S., Rajamanickam, R., McKee, T., “A Sensate Liner for Personnel Monitoring Applications”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 98-105, Cambridge, MA, USA, October 13-14, 1997.

[103] Lindgaard, G., “Usability Testing and System Evaluation a Guide for Designing Useful Computer Systems”, Chapman & Hall, London, UK, 393 pages, 1994.

[104] Linz, T., Kallmayer, C., Aschenbrenner, R., Reichl, H., “Embroidering Electrical Interconnects with Conductive Yarn for the Integration of Flexible Electronic Modules into Fabric”, Ninth IEEE International Symposium on Wearable Computers (ISWC ´05), pp. 86-89, Osaka, Japan, October 18-21, 2005.

[105] Long, A. C. Jr., Landay, J. A., Rowe, L. A., Michiels, J., “Visual Similarity of Pen Gestures”, Conference on Human Factors in Computing Systems (CHI 2000), ACM, pp. 360-367, The Hague, The Netherlands, April 1-6, 2000.

[106] Lukowicz, P., Anliker, U., Tröster, G., Schwartz, S. J., DeVaul, R. W., “The WearARM Modular, Low-Power Computing Core”, IEEE Micro, Vol. 21, No. 3, pp. 16-28, May-June 2001.

[107] Lukowicz, P., Anliker, U., Ward, J., Tröster, G., Hirt, E., Neufelt, C., “AMON: A Wearable Medical Computer for High Risk Patients”, Sixth IEEE International Symposium on Wearable Computers (ISWC ´02), pp. 133-134, Seattle, WA, USA, October 7-10, 2002.

[108] Lyons, K., Plaisted, D., Starner, T., “Expert Chording Text Entry on the Twiddler One-handed Keyboard”, Eighth IEEE International Symposium on Wearable Computers (ISWC ´04), pp. 94-101, Arlington, VA, USA, October 31-November 3, 2004.

[109] Lyons, K., Starner, T., “Mobile Capture for Wearable Computer Usability Testing”, Fifth IEEE International Symposium on Wearable Computers (ISWC ´01), pp. 69-76, Zürich, Switzerland, October 8-9, 2001.

[110] MacKenzie, I. S., Zhang, S. X., “The Design and Evaluation of a High-performance Soft Keyboard”, Conference on Human Factors in Computing Systems (CHI 99), ACM, pp. 25-31, Pittsburgh, PA, USA, May 15-20, 1999.

[111] Mackenzie, K., Hudson, E., Maule, D., Jayaraman, S., Park, S., “A Prototype Network Embedded in Textile Fabric”, International Conference on Compilers, Architecture and Synthesis for Embedded Systems (CASES’01), ACM, pp.188-194, Atlanta, GA, USA, November 16-17, 2001.

[112] Maekawa, T.; Nishimoto, K.; Mase, K.; Tadenuma, M.; ”A Wireless, Networked Musical Environment Consisting of Wearable MIDI Instruments”, 10th International Conference on Telecommunications (ICT’2003), IEEE, Vol. 2, pp. 1731-1734, Tahiti, French Polynesia, February 23- Marc 1, 2003.

[113] Mangione-Smith, W. H., “Mobile Computing and Smart Spaces”, IEEE Concurrency, Vol. 6, No. 4, pp. 5-7, October-December, 1998.

[114] Mann, S., “”Smart Clothing”: Wearable Multimedia Computing and “Personal Imaging” to Restore the Technological Balance Between People and Their Environments”, Fourth ACM International Conference on Multimedia (Multimedia ´96), pp. 163-174, Boston, MA, USA, November 18-22, 1996.

[115] Mann, S., “An Historical Account of the ‘WearComp’ and ‘WearCam’ Inventions Developed for Applications in ‘Personal Imaging’”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 66-73, Cambridge, MA, USA, October 13-14, 1997.

[116] Mann, S., “Eudaemonic Computing (‘underwearables’)”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 177-178, Cambridge, MA, USA, October 13-14, 1997.

[117] Mann, S., “Fundamental Issues in Mediated Reality, WearComp, and Camera-Based Augmented Reality”, Barfield, W. & Caudell, T. (eds.), “Fundamentals of Wearable Computers and Augmented Reality”, Lawrence Erlbaum Associates, Mahwah, New Jersey, USA, pp. 295-328, 2001.

[118] Mann, S., “Humanistic Computing: “WearComp” as a New Framework and Application for Intelligent Signal Processing”, Proceedings of the IEEE, Vol. 86, No. 11, pp. 2123-2151, November 1998.

[119] Mann, S., “Smart Clothing: The Shift to Wearable Computing”, Communications of the ACM, Vol. 39, No. 8, pp. 23-24, August 1996.

[120] Mann, S., “Wearable Computing: A First Step Toward Personal Imaging”, Computer, IEEE, Vol. 30, No. 2, pp. 25-32, February 1997.

[121] Mann, S., “Wearable Computing: Toward Humanistic Intelligence”, IEEE Intelligent Systems, Vol. 16, No. 3, pp. 10-15, 2001.

[122] Marculescu, D., Marculescu, R., Khosla, P. K., “Challenges and Opportunies in Electronic Textiles Modeling and Optimization”, 39th Annual ACM IEEE Conference on Design Automation, pp. 175-180, New Orleans, LA, USA, June 10-14, 2002.

[123] Marculescu, D., Marculescu, R., Zamora, N. H., Stanley-Marbell, P., Khosla, P. K., Park, S., Jayaraman, S., Jung, S., Lauterbach, C., Weber, W., Kirstein, T., Cottet, D., Grzyb, J., Tröster, G., Jones, M., Martin, T., Nakad, Z., “Electronic Textiles: A Platform for Pervasive Computing”, Proceedings of the IEEE, Vol. 91, No. 12, pp. 1995-2018, December 2003.

[124] Martin, T. L., “Time and Time Again: Parallels in the Development of the Watch and the Wearable Computer”, Sixth IEEE International Symposium on Wearable Computers (ISWC ´02), pp. 5-11, Seattle, WA, USA, October 7-10, 2002.

[125] Martin, T. L., Siewiorek, D. P., “Non-ideal Battery Properties and Low Power Operation in Wearable Computing”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 101-106, San Francisco, CA, USA, October 18-19, 1999.

[126] Martin, T., Jovanov, E., Raskovic, D., “Issues in Wearable Computing for Medical Monitoring Applications: A Case Study of a Wearable ECG Monitoring Device”, Fourth IEEE International Symposium on Wearable Computers (ISWC ´00), pp. 43-48, Atlanta, GA, USA, October 16-17, 2000.

[127] Matias, E., MacKenzie, S. I., Buxton, W., “Half-QWERTY: A One-handed Keyboard Facilitating Skill Transfer from QWERTY”, Conference on Human Factors in Computing Systems (CHI’93), ACM, pp. 88-94, Amsterdam, The Netherlands, April 24-29, 1993.

[128] Mazé, R., Jacobs, M., “Sonic City: Prototyping a Wearable Experience”, Seventh IEEE International Symposium on Wearable Computers (ISWC ´03), pp. 160-163, White Plains, NY, USA, October 21-23, 2003.

[129] McCann, J., Hurford, R., Martin, A., “A Design Process for the Development of Innovative Smart Clothing that Addresses End-User Needs from Technical, Functional, Aesthetic and Cultural View Points”, Ninth IEEE International Symposium on Wearable Computers (ISWC ´05), pp. 70-77, Osaka, Japan, October 18-21, 2005.

[130] Melzer, J. E., Moffitt, K., “Head Mounted Displays Designing for the User”, McGraw-Hill, USA, 352 pages, 1997.

[131] Meoli, D., Plumlee-May, T., “Interactive Electronic Textile Development: A Review of Technologies”, Journal of Textile and Apparel, Technology and Management, North Carolina State University, USA, Vol. 2, No. 2, pp. 1-12, Spring 2002.

[132] Michahelles, F., Schiele, B., “Sensing and Monitoring Professional Skiers”, IEEE Pervasive Computing, Vol. 4, No. 3, pp. 40-46, July-September 2005.

[133] Microvision, “Virtual Retinal Display Technology”, 17^{th} Digital Avionics Systems Conference (DASC), IEEE, Vol. 1, pp. D35/1-D35/6, Bellevue, WA, USA, October 31-November 7, 1998.

[134] Mikkonen, J., Vanhala, J., Reho, A., Impiö, J., “Reima Smart Shout Concept and Prototype”, Fifth IEEE International Symposium on Wearable Computers (ISWC ´01), pp. 174-175, Zürich, Switzerland, October 8-9, 2001.

[135] Mizell, D., “Message from the General Chair”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. ix-x, San Francisco, CA, USA, October 18-19, 1999.

[136] Najjar, L. J., Thompson, J. C., Ockerman, J. J., “A Wearable Computer for Quality Assurance Inspectors in a Food Processing Plant”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 163-164, Cambridge, MA, USA, October 13-14, 1997.

[137] Narayanaswami, C., Raghunath, M. T., “Designing a New Form Factor for Wearable Computing”, IEEE Pervasive Computing, Vol. 1, No. 4, pp. 42-48, October-December 2002.

[138] Naya, F., Noma, H., Ohmura, R., Kogure, K., “Bluetooth-based Indoor Proximity Sensing for Nursing Context Awareness”, Ninth IEEE International Symposium on Wearable Computers (ISWC ´05), pp. 212-213, Osaka, Japan, October 18-21, 2005

[139] Nielsen, J., “Usability Engineering”, AP Professional, Boston, USA, 362 pages, 1993.

[140] Nishimoto, K., Maekawa, T., Tada, Y., Mase, K., Nakatsu, R., “Networked Wearable Musical Instruments Will Bring a New Musical Culture”, Fifth IEEE International Symposium on Wearable Computers (ISWC ´01), pp. 55-62, Zürich, Switzerland, October 8-9, 2001.

[141] Norman, D. A., “The Design of Everyday Things”, Doubleday, New York, USA, 257 pages, 1990.

[142] Ockerman, J. J., Najjar, L. J., Thompson, J. C., “Wearable Computers for Performance Support: Initial Feasibility Study”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 10-17, Cambridge, MA, USA, October 13-14, 1997.

[143] Ockerman, J. J., Pritchett, A. R., “Preliminary Investigation of Wearable Computers for Task Guidance in Aircraft Inspection”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 33-40, Pittsburgh, PA, USA, October 19-20, 1998.

[144] Orth, M., Post, R., Cooper, E., “Fabric Computing Interfaces”, Conference on Human Factors in Computing Systems (CHI 98), ACM, pp. 331-332, Los Angeles, CA, USA, April 18-23, 1998.

[145] Ottenbacher, J., Römer, S., Kunze, C., Grossmann, U., Stork, W., “Integration of a Bluetooth Based ECG System into Clothing”, Eighth IEEE International Symposium on Wearable Computers (ISWC ´04), pp. 186-187, Arlington, VA, USA, October 31-November 3, 2004.

[146] Paradiso, J. A., Hsiao, K., Benbasat, A. Y., Teegarden, Z., “Design and Implementation of Expressive Footwear”, IBM Systems Journal, Vol. 39, No. 3/4, pp. 511-529, 2000.

[147] Paradiso, J. A., Hu, E., “Expressive Footwear for Computer-Augmented Dance Performance”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 165-166, Cambridge, MA, USA, October 13-14, 1997.

[148] Paradiso, J. A., Starner, T., “Energy Scavenging for Mobile and Wireless Electronics”, IEEE Pervasive Computing, Vol. 4, No. 1, pp. 18-27, January-March 2005.

[149] Paradiso, R., Loriga, G., Taccini, N., “Wearable System for Vital Signs Monitoring”, Lymberis, A. & de Rossi, D. (Eds.), “Wearable eHealth Systems for Personalised Health Management”, IOS Press, Amsterdam, the Netherlands, Vol. 108, pp. 253-259, 2004.

[150] Park, S., Jayaraman, S., “Enhancing the Quality of Life Through Wearable Technology”, IEEE Engineering in Medicine and Biology Magazine, Vol. 22, No. 3, pp. 41-48, May-June 2003.

[151] Parsons, K. C., “Human Thermal Environments”, Taylor & Francis Ltd., London, UK, 359 pages, 1993.

[152] Pavlovych, A., Stuerzlinger, W., “Less-Tap: A Fast and Easy-to-learn Text Input Technique for Phones”, Graphics Interface (GI 2003), A. K. Peters, pp. 97-104, Halifax, Nova Scotia, Canada, June 11-13, 2003.

[153] Pentland, A., “Smart Rooms, Desks, and Clothes”, International Conference on Acoustics, Speech, and Signal Processing (ICASSP-97), IEEE, Vol. 1, pp. 171-174, Munich, Germany, April 21-24, 1997.

[154] Pentland, A., “Smart Rooms, Smart Clothes”, 14th International Conference on Pattern Recognition (ICPR’98), IEEE, Vol. 2, pp. 949-953, Brisbane, Australia, August 16-20, 1998.

[155] Pfarr, B., Rice M. W., Fatic C.C., Green D., “Wearable Computers for NASA Applications”, IEEE Aerospace Conference, Vol. 7, pp. 3489-3497, Big Sky, MT, USA, March 10-17, 2001.

[156] Picard, R. W., “Affective Computing”, The MIT Press, Cambridge, MA, USA, 292 pages, 1997.

[157] Post, E. R., Orth, M., “Smart Fabric, or “Wearable Clothing””, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 167-168, Cambridge, MA, USA, October 13-14, 1997.

[158] Post, E. R., Orth, M., Russo, P. R., Gershenfeld, N., “E-Broidery: Design and Fabrication of Textile-based Computing”, IBM Systems Journal, Vol. 39, No. 3 and 4, pp. 840-860, 2000.

[159] Post, E. R., Reynolds, M., Gray, M., Paradiso, J., Gershenfeld, N., “Intrabody Buses for Data and Power”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 52-55, Cambridge, MA, USA, October 13-14, 1997.

[160] Preece, J., Rogers, Y., Sharp, H., Benyon, D., Holland, S., Carey, T., “Human-Computer Interaction”, Addison-Wesley, 775 pages, 1994.

[161] Press release of Apple, URL “ http://www.apple.com/pr/library/2003/jan/07burtonipod.html “, 29.7.2006.

[162] Raghunath, M. T., Narayanaswami, C., “User Interfaces for Applications on a Wrist Watch”, Personal and Ubiquitous Computing, Vol. 6, No. 1, pp. 17-30, February 2000.

[163] Ram, S., Sharf, J., “The People Sensor: A Mobility Aid for the Visually Impaired”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 166-167, Pittsburgh, PA, USA, October 19-20, 1998.

[164] Rekimoto, J., “GestureWrist and GesturePad: Unobtrusive Wearable Interaction Devices”, Fifth IEEE International Symposium on Wearable Computers (ISWC ´01), pp. 21-27, Zürich, Switzerland, October 8-9, 2001.

[165] Rhodes, B. J., “The wearable Remembrance Agent: A System for Augmented Memory”. First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 123-128, Cambridge, MA, USA, October 13-14, 1997.

[166] Rhodes, B. J., Minar, N., Weaver, J., “Wearable Computing Meets Ubiquitous Computing: Reaping the Best of Both Worlds”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 141-149, San Francisco, CA, USA, October 18-19, 1999.

[167] Ross, D. A., “Implementing Assistive Technology on Wearable Computers”, IEEE Intelligent Systems, Vol. 16, No. 3, pp.47-53, May-June 2001.

[168] Salonen, P., Hurme, H., “A Novel Fabric WLAN Antenna for Wearable Applications”, Antennas and Propagation Society International Symposium, IEEE, Vol. 2, pp. 700-703, Columbus, OH, USA, June 22-27, 2003.

[169] Salonen, P., Sydänheimo, L., Keskilammi, M., Kivikoski, M., ”A Small Planar Inverted-F Antenna for Wearable Applications”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 95-100, San Francisco, CA, USA, October 18-19, 1999.

[170] Sawhney, N.; Schmandt, C., “Speaking and Listening on the Run: Design for Wearable Audio Computing”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 108-115, Pittsburgh, PA, USA, October 19-20, 1998.

[171] Schmidt, A., Gellersen, H. W., Beigl, M., “A Wearable Context-Awareness Component Finally a Good Reason to Wear a Tie”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 176-177, San Francisco, CA, USA, October 18-19, 1999.

[172] Siegel, J., Bauer, M., “A Field Usability Evaluation of a Wearable System”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 18-22, Cambridge, MA, USA, October 13-14, 1997.

[173] Siewiorek, D., Smailagic, A., Bass, L., Siegel, J., Martin, R., Bennington, B., “Adtranz: A Mobile Computing System for Maintenance and Collaboration”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 25-32, Pittsburgh, PA, USA, October 19-20, 1998.

[174] Siewiorek, D., Smailagic, A., Furukawa, J., Krause, A., Moraveji, N., Reiger, K., Shaffer, J., Wong, F. L., “SenSay: A Context-Aware Mobile Phone”, Seventh IEEE International Symposium on Wearable Computers (ISWC ´03), pp. 248-249, White Plains, NY, USA, October 21-23, 2003.

[175] Smailagic, A., “ISAAC: A Voice Activated Speech Response System for Wearable Computers”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 183-184, Cambridge, MA, USA, October 13-14, 1997.

[176] Smailagic, A., Reilly, D., Siewiorek, D. P., “A System-level Approach to Power/Performance Optimization in Wearable Computers”, IEEE Computer Society Workshop on VLSI, pp. 15-20, Orlando, FL, USA, April 27-28, 2000.

[177] Smailagic, A:, Siewiorek, D., Bass, L., Iannucci, B., Dahbura, A., Eddleston, S., Hanson, B., Chang, E., “MoCCA: A Mobile Communication and Computing Architecture”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 64-71, San Francisco, CA, USA, October 18-19, 1999.

[178] Smailgic, A., Martin, R., “Metronaut: A Wearable Computer with Sensing and Global Communication Capabilities”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 116-122, Cambridge, MA, USA, October 13-14, 1997.

[179] Spitzer, M. B., Rensing, N. M., McClelland, R., Aquilino, P., “Eyeglass-Based Systems for Wearable Computing”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 48-51, Cambridge, MA, USA, October 13-14, 1997.

[180] Stanford, V., “Wearable Computing Goes Live in Industry”, IEEE Pervasive Computing, Vol. 1, No. 4, pp. 14-19, October-December 2002.

[181] Starner, T. E., “Powerful Change Part 1: Batteries and Possible Alternatives for the Mobile Market”, IEEE Pervasive Computing, Vol. 2, No. 4, pp. 86-88, October-December 2003.

[182] Starner, T. E., “The Enigmatic Display”, IEEE Pervasive Computing, Vol. 2, No. 1, pp. 15-18, January-March 2003.

[183] Starner, T. E., “Wearable Computers: No Longer Science Fiction”, IEEE Pervasive Computing, Vol. 1, No. 2, pp. 86-88, January-March 2002.

[184] Starner, T., “Human-powered Wearable Computing”, IBM Systems Journal, Vol. 35, No. 3/4, pp. 618-629, 1996.

[185] Starner, T., “The Challenges of Wearable Computing: Part 1”, IEEE Micro, Vol. 21, No. 4, pp. 44-52, July-August 2001.

[186] Starner, T., Kirsch, D., Assefa, S., “The Locus Swarm: An Environmentally-powered, Networkless Location and Messaging System”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 169-170, Cambridge, MA, USA, October 13-14, 1997.

[187] Starner, T., Weaver, J., Pentland, A., “A Wearable Computer Based American Sign Language Recognizer”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 130-137, Cambridge, MA, USA, October 13-14, 1997.

[188] Stein, R., Ferrero, S., Hetfield, M., Quin, A., Krichever, M., “Development of a Commercially Successful Wearable Data Collection System”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 18-24, Pittsburgh, PA, USA, October 19-20, 1998.

[189] Sung, M., DeVaul, R., Jimenez, S., Gips, J., Pentland, A., “Shiver Motion and Core Body Temperature Classification for Wearable Soldier Health Monitoring Systems”, Eighth IEEE International Symposium on Wearable Computers (ISWC ´04), pp. 192-193, Arlington, VA, USA, October 31-November 3, 2004.

[190] Sunkpho, J., Garrett, J. H., Smailagic, A., Siewiorek, D. P., “MIA: A Wearable Computer for Bridge Inspectors”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 160-161, Pittsburgh, PA, USA, October 19-20, 1998.

[191] Suomela, R., Lehikoinen, J., “Context Compass”, Fourth IEEE International Symposium on Wearable Computers (ISWC ´00), pp. 147-154, Atlanta, GA, USA, October 16-17, 2000.

[192] Syrjärinne, J., “Studies of Modern Techniques for Personal Positioning”, Doctor of Technology Thesis, Tampere University of Technology, 180 pages, March 2001.

[193] Tada, Y.; Nishimoto, K.; Maekawa, T.; Rouve, R.; Mase, K.; Nakatsu, R.; “Towards Forming Communities Using Wearable Musical Instruments”, 21st International Conference on Distributed Computing Systems (ICDCS-21), IEEE, pp. 260-265, Phoenix, AZ, USA, April 16-19, 2001.

[194] Tan, H. Z.; Pentland, A.; “Tactual Displays for Wearable Computing”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 84-89, Cambridge, MA, USA, October 13-14, 1997.

[195] Tao, X., “Smart Technology for Textiles and Clothing – Introduction and Overview”, Tao, X. (Ed.), “Smart Fibres, Fabrics and Clothing”, Woodhead Publishing Limited, Cambridge, England, pp.1-6, 2001.

[196] Thomas, B., Close, B., Donoghue, J., Squires, J., De Bondi, P., Morris, M., Piekarski, W., “ARQuake: An Outdoor/Indoor Augmented Reality First Person Application”, Fourth IEEE International Symposium on Wearable Computers (ISWC ´00), pp. 139-146, Atlanta, GA, USA, October 16-17, 2000.

[197] Thomas, B., Demczuk, V., Piekarski, W., Hepworth, D., Gunther, B., “A Wearable Computer System with Augmented Reality to Support Terrestrial Navigation”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 168-171, Pittsburgh, PA, USA, October 19-20, 1998.

[198] Thomas, B., Tyerman, S., Grimmer, K., ”Evaluation of Three Input Mechanisms for Wearable Computers”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 2-9, Cambridge, MA, USA, October 13-14, 1997.

[199] Thompson, C., Ockerman, J. J., Najjar, L. J., Rogers, E., ”Factory Automation Support Technology (FAST): A New Paradigm of Continuous Learning and Support Using a Wearable”, First IEEE International Symposium on Wearable Computers (ISWC ´97), pp. 31-38, Cambridge, MA, USA, October 13-14, 1997.

[200] Thorp, E. O., “The Invention of the First Wearable Computer”, Second IEEE International Symposium on Wearable Computers (ISWC ´98), pp. 4-8, Pittsburgh, PA, USA, October 19-20, 1998.

[201] Toney, A., Mulley, B., Thomas, B. H., Piekarski, W., “Minimal Social Weight User Interactions for Wearable Computers in Business Suits”, Sixth IEEE International Symposium on Wearable Computers (ISWC ´02), pp. 57-64, Seattle, WA, USA, October 7-10, 2002.

[202] Toney, A., Mulley, B., Thomas, B. H., Piekarski, W., “Social Weight: Designing to Minimise the Social Consequences Arising from Technology Use by the Mobile Professional”, Personal and Ubiquitous Computing, Springer-Verlag, Vol. 7, No. 5, pp. 309-320, October 2003.

[203] Van Langenhove, L., Hertleer, C., “Smart Clothing: A New Life”, International Journal of Clothing Science and Technology, Vol. 16, No. 1/2, pp. 63-72, 2004.

[204] Vanhala, J., “Wearable Technology Development in Finland”, Wearable Electronics and Smart Textiles Seminar, 7 pages, Leeds, UK, June 11, 2004. Paper available at URL = “ http://www.smartextiles.info/member_downloads.htm “, for Wearable Electronics & Smart Textiles (WEST) Interest Group, July 29, 2006.

[205] Velger, M., “Helmet-Mounted Displays and Sights”, Artech House, Norwood, MA, USA, 291 pages, 1998.

[206] Venkatasetty, H. V., Jeong, Y. U., “Recent Advances in Lithium-ion and Lithium-polymer Batteries”, 17th Annual Battery Conference on Applications and Advances, IEEE, pp. 173-178, Long Beach, CA, USA, January 15-18, 2002.

[207] Want, R., Pering, T., Borriello, G., Farkas, K. I., “Disappearing Hardware”, IEEE Pervasive Computing, Vol. 1, No. 1, pp. 36-47, January-March 2002.

[208] Weber, J. L., Blanc, D., Dittmar, A., Comet, B., Corroy, C., Noury, N., Baghai, R., Vaysse, S., Blinowska, A., “VTAMN – A New “Biocloth” for Ambulatory Telemonitoring”, Fourth Annual IEEE Conference on Information Technology Applications in Biomedicine (ITAB 2003), pp. 299-301, Birmingham, UK, April 24-26, 2003.

[209] Weber, J.-L., Blanc, D., Dittmar, A., Comet, B., Corroy, C., Noury, N., Baghai, R., Vaysse, S., Blinowska, A., “Telemonitoring of Vital Parameters with Newly Designed Biomedical Clothing”, Lymberis, A. & de Rossi, D. (Eds.), “Wearable eHealth Systems for Personalised Health Management”, IOS Press, Amsterdam, the Netherlands, Vol. 108, pp. 260-265, 2004.

[210] Webpages for electronics standards of textiles and leather, URL = http://webstore.ansi.org/ansidocstore/dept.asp?dept_id=420, 29.7.2006.

[211] Webpages of Burton snowboarding jacket, URL = " http://www.minidisc.org/part_Burton_Analog_Clone_MD_Snowboarding_Jacket.html ", 29.7.2006.

[212] Webpages of commVEST, URL " http://www.idsa.org/idea/idea2005/g818.htm ", 29.7.2006.

[213] Webpages of heating jacket, URL "http://www.bobwards.com/bobwards/servlet/item/features/104915-09 ", 29.7.2006.

[214] Webpages of Nokia group, URL = " http://nokia.com", 15.8.2006.

[215] Webpages of number 1 shoes, URL = " http://www.gizmag.co.uk/go/2810/ ", 29.7.2006.

[216] Webpages, of NIKE+ shoes, URL = " http://www.orangecone.com/archives/2006/05/nikeapple_smart.html ", 29.7.2006.

[217] Weilemann, A., Holmquist, L., E., "Hummingbirds Go Skiing: Using Wearable Computers to Support Social Interaction", Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 191-192, San Francisco, CA, USA, October 18-19, 1999.

[218] Weiser, M., "The Computer for the 21st Century", ACM SIGMOBILE Mobile Computing and Communications Review, Vol. 3, No. 3, pp.3-11, July 1999.

[219] Weiser, M., Brown, J. S., "The Coming Age of Calm Technology", 17 pages, Revised version of Weiser, M., Brown, J. S., "Designing Calm Technology", Powergrid Journal, July 1996, available at URL = " http://www.johnseelybrown.com/calmtech.pdf ", 27.7.2006.

[220] Weiss, S., "Handheld Usability", John Wiley & Sons, England, 271 pages, 2002.

[221] Werner, J. H., Wagner, T. A., Gemmer, C. E. M., Berge, C., Brendle, W., Schubert, M. B., "Recent Progress on Transfer-Si Solar Cells at ipe Stuttgart", Third World Conference on Photovoltaic Energy Conversion, IEEE, pp.1272-1275, Osaka, Japan, May 11-18, 2003.

[222] Wijesiriwardana, R., Dias, T., Mukhopadhyay, S., "Resistive Fibre-Meshed Transducers", Seventh IEEE International Symposium on Wearable Computers (ISWC ´03), pp. 200-209, White Plains, NY, USA, October 21-23, 2003.

[223] Wijesiriwardana, R., Mitcham, K., Dias, T., "Fibre-Meshed Transducers Based Real Time Wearable Physiological Information Monitoring System", Eighth IEEE International Symposium on Wearable Computers (ISWC ´04), pp. 40-47, Arlington, VA, USA, October 31-November 3, 2004.

[224] Wijnalda, G., Pauws, S., Vigoli, F., Stuckenschmidt, H., “A Personalized Music System for Motivation in Sport Performance”, IEEE Pervasive Computing, Vol. 4, No. 3, pp. 26-32, July-September 2005.

[225] Willis, S., Helal, S., “RFID Information Grid for Blind Navigation and Wayfinding”, Ninth IEEE International Symposium on Wearable Computers (ISWC ´05), pp. 34-37, Osaka, Japan, October 18-21, 2005.

[226] Xybernaut Corporation, Fairfax, VA, USA, Mobile Assistant V (MA V) Brochure, Available at URL = “ http://www.xybernaut.com/assets/files/site_content/PDFs/Brochures/XYB_MAV.pdf “, 29.7.2006.

[227] Yang, J., Yang, W., Denecke, M., Waibel, A., “Smart Sight: A Tourist Assistant System”, Third IEEE International Symposium on Wearable Computers (ISWC ´99), pp. 73-, San Francisco, CA, USA, October 18-19, 1999.

[228] Yoshinori, K., Yasuko, S., “What is Environmental Testing?”, Espec Technology Report no. 1, 32 pages, Osaka, Japan, 1996. Availabale at URL http://www.espec.co.jp/image/english/pdf/technoe1.pdf, 15.8.2006.

[229] Zhai, S., Sue, A., Accot, J., “Movement Model, Hits Distribution and Learning in Virtual Keyboarding”, Conference on Human Factors in Computing Systems (CHI 2002), ACM, pp. 17-24, Minneapolis, MN, USA, April 20-25, 2002.

[230] Zieniewicz, M. J., Johnson, D. C., Wong, D. C., Flatt, J. D., “The Evolution of Army Wearable Computers”, IEEE Pervasive Computing, Vol. 1, No. 4, pp. 30-40, October-December 2002.

[231] Zimmerman, T. G., “Wireless Networked Digital Devices: A New Paradigm for Computing and Communiation”, IBM Systems Journal, Vol. 38, No. 4, pp. 566-574, 1999.

Publications

Publication [P1]

Rantanen, J., Impiö, J., Karinsalo, T., Malmivaara, M., Reho, A., Tasanen, M., Vanhala, J., "Smart Clothing Prototype for the Arctic Environment", Personal and Ubiquitous Computing, Springer-Verlag, Vol. 6, No. 1, pp. 3-16, 2002.

Publication [P2]

Rantanen, J., Reho, A., Tasanen, M., Karinsalo, T., Vanhala, J., ”Monitoring of the User’s Vital Functions and Environment in Reima Smart Clothing Prototype”, Arai, E., Arai, T. & Takano, M. (Eds.), “Human Friendly Mechatronics”, Elsevier, Amsterdam, pp. 25-30, 2001.

Publication [P3]

Rantanen, J., Ryynänen, O., Kukkonen, K., Vuorela, T., Siili A., Vanhala, J., ”Electrically Heated Clothing”, Fifth World Multi-Conference on Systemics, Cybernetics and Informatics, IIS and IFSR, pp. 490-495, Orlando, FL, USA, July 22-25, 2001.

Publication [P4]

Rantanen, J., Vuorela, T., Kukkonen, K., Ryynänen, O., Siili, A., Vanhala, J., "Improving Human Thermal Comfort with Smart Clothing", IEEE Systems, Man, and Cybernetics Conference, pp. 795-800, Tucson, AZ, USA, October 7-10, 2001.

Publication [P5]

Rantanen, J., Alho, T., Kukkonen, K., Vuorela, T., Vanhala, J., ”Wearable Platform for Outdoor Positioning”, Fourth International Conference on Machine Automation (ICMA 2002), pp. 347-357, Tampere, Finland, September 11-13, 2002.

Publication [P6]

Hännikäinen, J., Vuorela, T., Vanhala, J., “Physiological Measurements in Smart Clothing: A Case Study of Total Body Water Estimation with Bioimpedance”, Transactions of the Institute of Measurement and Control, Hodder Arnold, 2006/2007, Accepted.

Publication [P7]

Rantanen, J., Jokinen, E., Reini, J., Vanhala, J., "Usability Study of CityGuide: A Mobile Mapping Application", Ninth IEEE International Conference on Telecommunication (ICT 2002), pp. 553-558, Beijing, China, June 23-26, 2002.

Publication [P8]

Rantanen, J., Hännikäinen, M., “Data Transfer for Smart Clothing: Requirements and Potential Solutions”, Tao, X. (Ed.), “Wearables and Photonics”, Woodhead Publishing, England, pp. 198-222, 2005.

Publication [P9]

Hännikäinen, J., Järvinen, T., Vuorela, T., Vähäkuopus, K., Vanhala, J., "Conductive Fibres in Smart Clothing Applications", Fifth International Conference on Machine Automation (ICMA 2004), pp. 227-232, Osaka, Japan, November 24-26, 2004. Accepted for publication as a book chapter in Mechatronics for Safety, Security and Dependability in a New Era, Elsevier.

Publication [P10]

Hännikäinen, J.; Mikkonen, J.; Vanhala, J., ”Button component encasing for wearable technology applications”, Ninth IEEE International Symposium on Wearable Computers (ISWC ’05), pp. 204-205, Osaka, Japan, October 18-21, 2006.

Publication [P11]

Salonen, P., Rantanen, J., “A Dual-Band Antenna on Flexible Substrate for Smart Clothing”, 27th Annual Conference of the IEEE Industrial Electronics Society, pp. 125-130, Denver, CO, USA, November 29-December 2, 2001.