Tampere University

ADNAN MEHMOOD

Clothing-Integrated Human-Technology Interaction

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ACADEMIC DISSERTATION
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the Faculty of Medicine and Health Technology
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To my parents and wife

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Tampere, 2022

Adnan Mehmood

ABSTRACT

Due to the different disabilities of people and versatile use environments, the current handheld and screen-based digital devices on the market are not suitable for all consumers and all situations. Thus, there is an urgent need for human-technology interaction solutions, where the required input actions to digital devices are simple, easy to establish, and instinctive, allowing the whole society to effortlessly interact with the surrounding technology.

In passive ultra-high frequency (UHF) radio frequency identification (RFID) systems, the tag consists only of an antenna and a simple integrated circuit (IC). The tag gets all the needed power from the RFID reader and can be thus seamlessly and in a maintenance-free way integrated into clothing.

In this thesis, it is presented that by integrating passive UHF RFID technology into clothing, body movements and gestures can be monitored by monitoring the individual IDs and backscattered signals of the tags. Electro-textiles and embroidery with conductive thread are found to be suitable options when manufacturing and materials for such garments are considered. This thesis establishes several RFID-based interface solutions, multiple types of inputs through RFID platforms, and controlling the surrounding and communicating with RFID-based on/off functions.

The developed intelligent clothing is visioned to provide versatile applications for assistive technology, for entertainment, and ambient assistant living, and for comfort and safety in work environments, just to name a few examples.

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ABBREVIATIONS

AAC	Alternative and Assistive Communications
EIRP	Effective Isotropic Radiated Power
EPC	Electronic Product Code
EPDM	Ethylen Propylen Diene Monomer
HF	High Frequency
HTI	Human Technology Interaction
IC	Integrated Circuit
IoT	Internet of Things
LF	Low Frequency
M6	Mercury 6
RFID	Radio Frequency Identification
UHF	Ultra-High Frequency
USB	Universal Serial Bus

ORIGINAL PUBLICATIONS

Publication I A. Mehmood, S. Qureshi, H. He, X. Chen, S. Ahmed, S. Merilampi, P. Raumonen, L. Ukkonen, and J. Virkki, "Clothing-Integrated RFID-based Interface for Human-technology Interaction," 2019 IEEE 7th International Conference on Serious Games and Applications for Health (SeGAH), Kyoto, Japan, pp. 1-5, doi: 10.1109/SeGAH.2019.8882467, 2019.

Publication II A. Mehmood, H. He, X. Chen, S. Merilampi, L. Sydänheimo, L. Ukkonen, and J. Virkki, "Body Movement-Based Controlling Through Passive RFID Integrated into Clothing," IEEE Journal of Radio Frequency Identification, vol. 4, no. 4, pp. 414-419, doi: 10.1109/JRFID.2020.3010717, 2020.

Publication III A. Mehmood, H. He, X. Chen, A. Vianto, O. Buruk, and J. Virkki, "ClothFace: Battery-Free User Interface Solution Embedded into Clothing and Everyday Surroundings," 2020 IEEE 8th International Conference on Serious Games and Applications for Health (SeGAH) Vancouver, Canada, pp. 1-5, doi: 10.1109/SeGAH49190.2020.9201771, 2020.

Publication IV A. Mehmood, V. Vianto, H. He, X. Chen, O. Buruk, L. Ukkonen, and J. Virkki, "Passive UHF RFID-based User Interface on a Wooden Surface," Progress in Electromagnetics Research Symposium (PIERS), Xiamen, China, pp. 1760-1763, doi: 10.1109/PIERS-Fall48861.2019.9021441, 2019.

Publication V A. Mehmood, H. He, X. Chen, A. Vianto, V. Vianto, O. Buruk, and J. Virkki, "ClothFace: A Passive RFID-based Human-Technology Interface on a Shirtsleeve," Advances in Human-Computer Interaction (Hindawi), vol. 2020, Article ID:8854042, doi: 10.1155/2020/8854042, 2020.

Publication VI A. Mehmood, H. He, X. Chen, A. Vianto, V. Vianto, and J. Virkki, "ClothFace: A Batteryless Glove-Integrated User Interface Solution based on Passive UHF RFID Technology," 2020 IEEE 8th International Conference on Serious Games and Applications for Health (SeGAH),

Vancouver, Canada, pp. 1-5, doi: 10.1109/SeGAH49190.2020.9201793, 2020.

Publication VII A. Mehmood, H. He, X. Chen, Z. Khan, T. Ihalainen, and J. Virkki, "Development, Fabrication and Evaluation of Passive Interface Gloves," Textile Research Journal, doi:10.1177/00405175211019132, 2021.

Publication VIII A. Mehmood, Z. Khan, A. Vianto, T. Ihalainen, and J. Virkki, "Passive RFID-based Intelligent Gloves for Alternative and Assistive Communication–A Preliminary Study," in IEEE AP-S/URSI, May 2021.

AUTHOR CONTRIBUTIONS

Publication I	The author is the main contributor of this publication. The designing, fabrication, and testing of the interfaces was carried out by the author. The manuscript was written by the author and was modified and revised by Sari Merilampi, Pasi Raumonen, and Johanna Virkki. Other co-authors helped in testing, taking the pictures, and reviewing the text.
Publication II	The author is the main contributor of this publication. The author designed and manufactured the interface. The measurements were carried out with help of co-authors. The manuscript was written by author. It was revised and modified by Sari Merilampi and Johanna Virkki. The text was reviewed by other co-authors as well.
Publication III	The author is the main contributor of this publication. The interface solution was designed and manufactured by the author. The testing software was designed by Aleksi Vianto. The measurements were carried out with the help of co-authors. The manuscript was written by the author. It was revised and modified by Johann Virkki and Oğuz 'Oz' Buruk.
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Publication V	The author is the main contributor of this publication. The user interface was designed and fabricated by the author. The testing software was made by Aleksi Vianto and Ville Vianto. The measurements were carried out with the help of the co-authors. The author wrote the manuscript, which was revised and modified by Johanna Virkki.
Publication VI	The author is the main contributor of this publication. The author designed and fabricated the glove. The manuscript was written by the author. The testing was carried out by the co-authors and manuscript was reviewed and modified by the co-authors as well.

Johanna Virkki revised and modified the final manuscript for submission.

Publication VII The author is the main contributor of this publication. Zahangir Khan helped with the measurements while Aleksi Vianto designed the testing software. The manuscript was written by the author. Tiina Ihalainen and Johanna Virkki supervised the publication, revised, and modified the final manuscript for submission.

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1 INTRODUCTION

The human–technology interaction (HTI) has taken a larger role in organizing our daily life matters [1] [2] [3], leading with applications of smart homes [4] [5] [6], playing games [7] [8] [9], interactive devices for disabled people [10] [11] [12] [13], health monitoring [14] [15] [16], rehabilitation exercises [17] [18] [19], and increased possibilities of acquiring new expertise. The conventional input methods (keyboard and mouse, touchpad, touchscreen) for human–technology interaction have recently been supported with gesture-based [20] [21] [22] [23] [24] and voice–based controlling [25] [26] [27] [28]. While talking about the human technology interaction there are some common voice controlled virtual assistants operating for daily usage such as Google Assistant [29], Microsoft's Cortana [30], Amazon's Alexa [31], and Apple's Siri [32]. The above digital devices are voice-operated and have certain limitations [33], which include challenges in noisy environments and quietness requiring environments, limited language assistance, unavailability to speech–impaired people. There are some body-centric—usually touch, gesture-, or body movement–based—human–technology interaction devices that are commercially available, such as Jacquard by Google [34], Sony PlayStation Move [35], Kinect from Microsoft [36], and Nintendo Wii Remote [37]. Furthermore, there are commercially available gaming/entertainment controllers and other interactive devices based on gestural/body movement using, for example, different sensors; these devices, such as those presented in [38] [39] [40] [41] [42] [43] [44], have gained a lot of interest among researchers and users. The challenges of these available solutions include complex and expensive sensors (wearable and camera-based), line of sight to operate or on-board energy source, high-maintenance cost limit, and lower adaptability, which limits its practical usage in high-scale applications and daily use. Further, a certain segment is easily deprived of the modern human–technology interaction because of the special needs of disabled persons [45] [46], such as people with cognitive, motoric, or language disabilities. Therefore, the interest is gathered around fabric-integrated controllers for human–technology interaction [47] [48] [49] [50] [51]. By integrating the human–technology solution to a desired placement on our daily clothing, individually tailored interaction solutions can follow the person everywhere. However, these interactive devices also still have the same challenges as all other technology solutions including power on-body sources or the user's having to directly face the device while using it and frequent maintenance. The technology to overcome these challenges and provide simple interaction capabilities for the sensing of human body gestures through Wi-Fi wireless signals–based devices for smart home, human wellbeing, and gaming applications [52] [53] [54] [55] has the potential to provide better alternatives. However, these solutions have challenges with multiple user environments, and they are configuration-dependent and only useful in a specific-use environment; thus, they cannot be taken outside [56] [57] [58].

The technology is constantly evolving, and the existing challenges are being addressed by novel solutions. This thesis introduces the eminent contactless passive ultra-high frequency (UHF) radio frequency identification (RFID) technology to resolve the challenges. The technology is passive in nature and, thus, highly cost effective because it draws all the needed power to operate from the RFID reader antenna and responds by backscattering the signal. This RFID technology consists of remotely accessible RFID tags comprised of an RFID integrated circuitry (IC) with a unique identity code and small antenna. Furthermore, the technology has a read range of several meters.

RFID has been commonly and effectively used in supply chain management [59] [60] [61] [62] and tracking and identification of items [63] [64] [65]. As the technology is evolving and smart controlling through wireless technologies is increasing, the smart shopping system through RFID technology [66] is a way forward toward smart and intelligent internet of things (IoT) systems. Additionally, RFID has been used to track people; for example, identifying and tracking children through a proposed RFID-based locater system [67] is an example of advanced study of this subject.

However, the potential of this technology goes beyond the purpose of tracking and identification. The integration of passive RFID tags into items, objects, and clothing is a major step toward future smart and intelligent systems. Previously, the change in backscattered signal due to, e.g., temperature and moisture changes have been an area of greater interest, as passive RFID tags have been used as independent temperature [68] [69] [70] [71] and moisture [72] [73] [74] sensors. In addition, the successful implementation of these sensors encouraged the integration of these tags for body movement and gestural sensors by following the changes in the backscattered signals caused by human body movements [75] [76] [77]. The above passive RFID tag–based body and gesture tracking results are useful in specific environments, especially when used from one fixed direction. However, they show that the backscattered signals of passive RFID tags are noisy, unstable, and strongly affected by the environment. Thus, alternative solutions are needed that are simpler, more reliable, and not as dependent on the noisy and unstable signals. Further, clothing is an essential part of human life and is a way to express oneself. Thus, innovative solutions for seamlessly integrating interactive devices in daily clothes for human technology interaction are needed. It is important for the technology to be available in different types of clothing for different types of people.

2 REVIEW OF LITERATURE

2.1 Human–technology interaction (HTI)

The interaction between human and computer is tracked back to 1945, when scientists and researchers started thinking of the new ways that we humans will interact with the machines around us [78]. But with the advancement in technology and the development of digital devices, the interaction between humans and technology became evident.

2.1.1 Human–technology interaction in our daily lives

The growth of the digital world around our traditional world has revolutionized the interaction modalities between humans and technology. The lifestyles of people are evolving with the advancement of technology and increased dependency on it. This dependency has brought many advantages, for example, the Internet of Things (IoT) has allowed us to convert a conventional home into a smart home [79], which allows us to control many home devices (home appliances, entertainment systems, computers, and metering systems) [80] [81]. A typical smart home's appliance control is shown in Figure 1. The IoT is the future of technology, and it will wirelessly interconnect humans and their surroundings; tracking and localizing moveable objects [82], a vehicle monitoring system [83], and a smart kitchen [84] are few examples of this advancement.

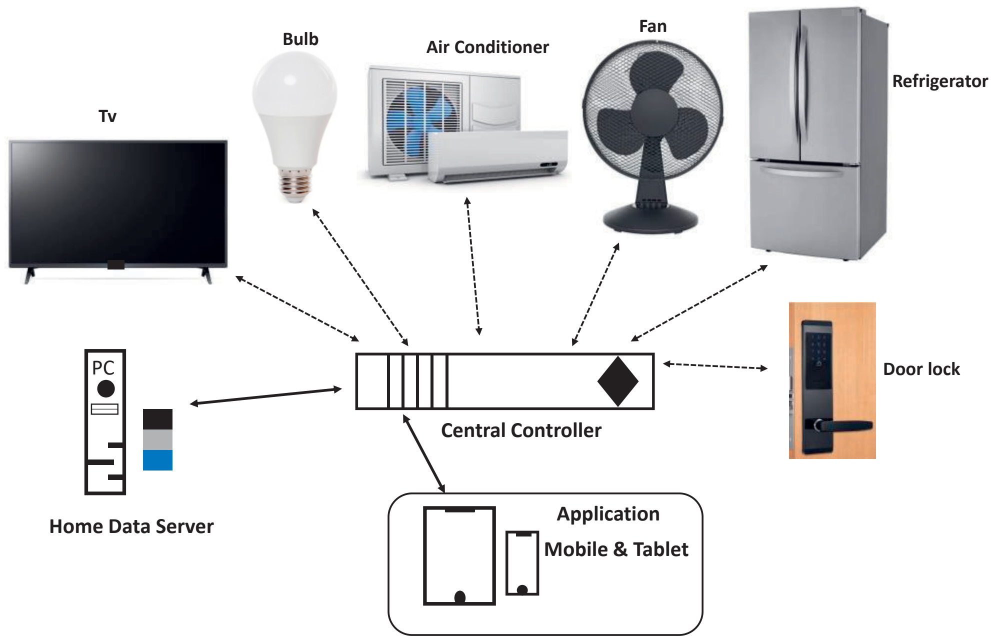

Figure 1. A typical home appliance control in a smart home.

We are becoming more dependent on technology [85], so investment in the betterment of human-technology interaction is needed. Reliance on cables for communication between humans and devices decreased after the development of wireless technology. Currently, digital devices are our gateway to the world around us. Through our mobile phones, tablets, and computers, we are able to communicate and participate [86] [87], play games [88] [89], organize our lives [90] [91], and learn new things [92] [93]. Mobile devices are also playing a larger role in health monitoring, along with their increasing use for controlling the technology around us, which has made mobile devices crucial for our everyday lives.

The method of interacting with the digital device, how it responds, and the subject of interaction is known as interface [94]. The interactive part of the technology system operated by humans is called user interface [95]. The user interface should be designed according to the needs of users and requirements of the computer system. The clarity of the simple design for user interface makes the control, operating function (fast and accurate), and reliability of output the most important factors for human–technology interaction (HTI) [95] [94]. The user interfaces [96] [97] are operated for example through gestures, hands, body, feet, and voice, just to name a few examples.

The advancement in methods of HTI is based on the old concepts of input, and gradually different technologies are replacing those old interactive devices [98]. The input methods into user interface are important to engage the user by introducing aesthetics, fun, and excitement in the designs [99]. The business models of commercially available applications (games, social media platforms) [100] [101] are based on how much time a user is spending on the screen. The key role of engaging the user with technology dependent on the nature of input methods; when the user is physically engaged with digital devices [102], they feel more attracted to them. The user's needs, behaviors, and situation based on the usage of the interactive devices act as an essential part of HTI development [103]. The physical, social, and self-actualization needs of the user are meant to be met in all HTI solution designs [104].

In addition to the traditional user interfaces, such as screen-based interaction methods, there are more creative methods of interacting with technology based on, for example, facial recognition, viewpoint, speech recognition, vision, and physical inputs [105] [106] [107] [108] [109]. However, the screen-based and touch-operated HTI has been the popular interactive solution for many currently available devices. The screen-based input in many interactive devices [110] [111] [112] [113] has been acknowledged and has widely supported the users' needs. The touch screen provides a finger-based gestural natural input solution [114] [115], which is suitable for most people. However, this causes challenges [116] [117][105] when focusing on a task or having both hands occupied, or physical challenges when walking or cycling, not to mention it being forbidden when driving. Further, some users have limited access to these solutions. These limitations could be on the user end due to limited knowledge of technology, disability of the user, or nature of the user environment. For example, dry fingertips, bad eyesight, and decreased hand strength make it difficult to use the current mobile devices, preventing their great advantages for the whole society.

Due to the above-mentioned challenges, there are many studies about devices being developed to engage people with special needs and disabilities [118] [119] [120] [121]. Recent studies have for example focused on the development of advanced-input assistive technologies, integrated view-input interactive assistance [106], a smart e-stick for the visually impaired [10], a foot-controlled interaction assistant based on visual tracking [46], an ear based interaction [122] and movement- [123] and touch-controlled [124] devices. However, these devices provide efficient input and interaction possibilities for persons with special needs, but they are based on complex technologies with high-energy power sources integrated in the devices. These factors limit this technology to certain users. Further, the fabrication is not cost effective, and high maintenance is required for such devices; such interfaces are difficult to carry because of the heavy energy sources required for the operating the device. So, for the people with disabilities, it will be hard to operate such devices.

A yet another alternative is voice-based human-technology interaction [25] [26] [27] [28] [125], so interaction with devices in the mentioned special conditions is easy and efficient. While talking about the human–technology interaction, there are some common voice-controlled virtual assistants for daily usage, such as Google Assistant [29], Microsoft Cortana [30], Amazon's Alexa [31], and Apple's Siri [32]. However, also the above digital devices have certain limitations [33], which include challenges in noisy environments and in those requiring quiet environments, limited language assistance, and unavailability to speech-impaired people.

2.1.2 Body-centric human–technology interaction

Human-technology interaction solutions can be integrated into fabrics; these wearable solutions then solve many of the mentioned issues of different users with special needs and direct the advancement of technology toward the further development of body-centric human–technology interaction. Therefore, recently interest is gathered around fabric-integrated controllers for human–technology interaction [47] [48] [49] [50] [51]. The body surface always plays an important role in designing interactive devices for HTI, and this purpose is met through designed body centric-sensors and body implants [126]. Body-centric HTI is based on devices controlled by touch, gesture, or body movement; some interactive sleeves are shown as an example in Figure 2.

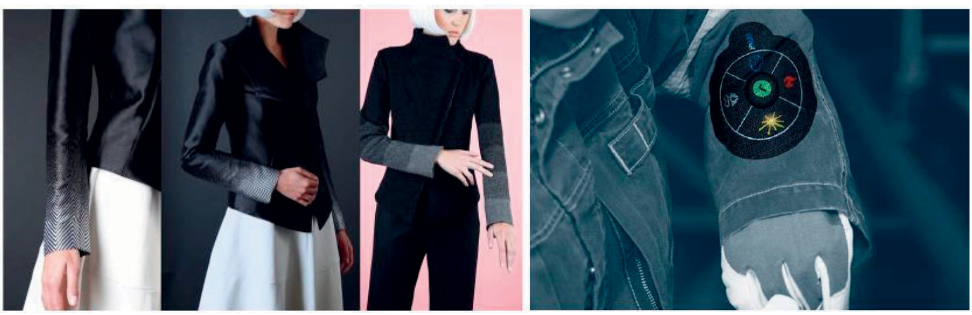

Figure 2. Project jacquard (left) [50] and interactive textile alert system (right) [51].

Many body-centric HTI solutions are commercially available, such as Jacquard by Google [34], Sony PlayStation Move [35], Kinect from Microsoft [36], and Nintendo Wii Remote [37]. Further, the commercially available gaming/entertainment controllers and other interactive devices based on gestural/body movement and using, e.g., sensors, such as those presented in [20] [21] [22] [23] [24] [127] [38] [39] [40] [41] [42] [43] [44], have gained a lot of interest among researchers and users. Different technologies have been suggested, for example, for detecting hand movement on the human body: acoustic and ultrasonic sensors [128] [129], infrared proximity sensors and reflective markers [41] [43], skin electronics [130], and interactive textiles [48] [49] [131] [132], for example, with conductive pads or lines connected to microcontrollers. Further, capacitive and resistive touch sensors have been successfully studied [122] [40]. It should be also noted that body-centric devices themselves have various applications in different sectors, e.g., healthcare [133] [134], smart homes [135] [136], daily life [137], entertainment [138], and gaming [139].

The input produced through the body (acts as an input device) always gives better feedback than an external input device, because the real feel of the body while touching enables the user experience off the computer screen, which is more attractive and engaging for the users. For example, a palm-based interface [140] allows the user to give input by pointing at a location on the palm using the finger; similarly, an ear surface is used to naturally create inputs for computer [122]. Further, finger taps on the arm can act as an input surface [129], touch-sensing provides a textile user interface solution [141], and a gesture-based abdomen input interface [142] are prime examples of touch and sense inputs. These body-centric solutions particularly provide an eye contact–free input interface and the touch and sense of the body itself provides the input surface. One advantage of body-centric inputs is that the device (the body) is always accessible. However, all these presented approaches need external electronics and power sources, which makes them complex, expensive, and, most of all, inconvenient when the goal is to integrate the human–mobile device interaction option into everyday clothing.

The technology to overcome these challenges is the sensing of human body gestures and movements through Wi-Fi signals [52] [53] [54] [55]. However, these solutions have challenges with multiple user environments, and they are configuration-dependent and only useful in a specific-use environment; thus, they cannot be taken outside, when the user is on the go [56] [57] [58].

2.2 RFID

2.2.1 RFID basics

Radio frequency identification (RFID) consists of an RFID tag antenna, integrated circuit (IC), and reader antenna. Initially, this RFID technology was excessively used in inventory applications to detect objects and other items for tracking [143] [144] [145] [146] because it is more efficient and effective than other identification technologies, i.e., barcode and QR code. The barcode and QR code need line of sight detection to properly identify the object by closely scanning it, but RFID technology does not need a line of sight or close-to-object operation.

There are three different types of RFID technology: active, passive, and semi passive [147]. The active RFID tags need a power source, which is a battery that powers the transmission to the reader. It has an active local power source and conventional transponders. Thus, these devices are known as bidirectional radio communication. Due to the active power source, the tags can be detected at a distance of several kilometers. Despite their long ranges, they have higher memories and less interference from the environment. There are drawbacks of this technology as well because it needs high power sources, but it is not cost effective as it requires timely maintenance (replacement of batteries) and larger sizes (not ideal for many applications) [148].

The semi-passive tags have a battery as an active power source. It needs power for its activation but can operate without any external power source after being activated. The range of these tags is smaller than the active tags, and they could be read a few meters from the reader antenna. These tags are also larger in size. It is not a cost-effective solution and requires maintenance of the power source [147].

The passive RFID tag does not need any external power source to activate the IC. These tags operate through the energy derived from the electromagnetic field generated by the reader antenna which has a power source and is constantly generating the radio waves. The passive tags use this energy to power the IC; then, it starts to generate the radio waves and transmits the signal to the reader antenna. These tags are smaller in size and cheaper to produce because they do not need an active power source. Thus, this technology is maintenance-free and highly efficient. But the read range of these tags is smaller than active and semi-passive. The comparison between active, semi passive, and passive RFID tags is shown in Table

1. The most famous passive RFID technology, which needs no external power source and is low cost [149], is currently being considered for versatile applications that are not only focused on detecting and tracking objects, e.g., sensors [150] [151]. The passive RFID technology has already been used for wireless controlling, positioning, and accessing [152] [153] [154] [155].

Table 1. Comparison of active, semi passive, and passive RFID tags

RFID tags	Power source	Read range	Cost
Active	Battery needed	Long	Expensive
Semi passive	Battery needed	Smaller than active tags	Less expensive than active tags
Passive	Not needed	Short	Cheap

The RFID readers and tags operate in different frequency ranges. The Low Frequency (LF), High Frequency (HF), and Ultra High Frequency (UHF) are the operational frequencies of different RFID transponders. These frequency ranges are meant for particular applications. The LF has band of 30-300 KHz, RFID LF systems operate at 125 KHz, and 134 KHz is intended for short-range applications [148]. These RFID tags are based on inductive coupling technology. The LF has a longer wavelength and can pass through heavy materials. The range of these devices is around a few inches and work only in close proximity. The typical applications of LF are car antitheft systems, animal identification, health care, and access control through RFID.

The HF has an allocated frequency band of 3–30 MHz. The HF RFID tags/readers operate at frequencies between 1.75 MHz and 13.56 MHz. These tags are passive in nature and do not need an active energy source. This technology is based on inductive coupling as RFID readers induce current in the RFID tags, and that power is then used to transmit the signal to the reader antenna through backscattered signal. The reader antennas operating at this frequency can read multiple tags simultaneously. This operatable frequency range is for the devices in smart labeling, tracking baggage/books, inventory stock tracking, and ticketing payments [148]. The typical working range of these devices is around 1 meter, which is higher than the LF devices.

The third and most famous operating frequency for most of the applications is UHF (300 MHz–1 GHz). The RFID readers and transponders in this range mostly work in (860–960 MHz) [148]. The RFID tags operating in this frequency range mostly have a read range of around 15 m, which is considerably higher than the devices operating in LF and HF. The properties of different RFID systems in different frequency ranges are described in Table 2. This technology, based on a backscatter coupling read speed of the reader antenna, is very fast. The readability of RFID readers operating in this range is much higher and can efficiently read multiple tags at once. The cost of the tags is very low, and they are smaller in comparison to the other two technologies. These tags operate at high frequency; therefore, the wavelength is smaller, so it does not work well near the metals. Some of the common applications are smart home devices, access controllers, object identification at long distance, and information transfer in large vicinities.

Table 2. Properties of different RFID systems in different frequency ranges

RFID system	Tag type	Technology	Frequency	Read range	Read speed	Cost
LF	Passive	Inductive coupling	125 KHz / 134 KHz	Short (few cm)	Slow	Low
HF	Passive	Inductive coupling	1.75–13.56 MHz	10 cm to 1 m	Fast	Low
UHF	Passive / semi passive / active	Backscatter coupling	860–960 MHz	Up to 15 m	Very fast	Very low

2.2.2 Passive UHF RFID in human–technology interaction

The passive UHF RFID technology that uses battery-free, remotely addressable electronic tags composed only of an antenna and a small IC component. Figure 3 shows a typical passive UHF RFID operating system, which includes a tag, reader antenna, reader, and computer operating system (showing the output on screen).

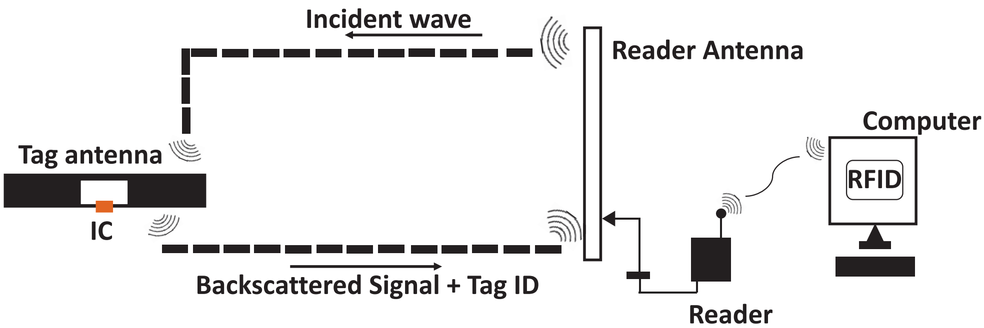

Figure 3. A typical passive UHF RFID operating system.

A real RFID operating system is shown in Figure 4. The IC stores the information related to the object by the tag antenna and passively communicates this information to the reader antenna by retrieving the necessary power to activate the IC through radio frequency waves from the reader antenna [156]. Each RFID IC has an Electronic Product Code (EPC), which is a universal identifier that gives a unique ID to a specific tag.

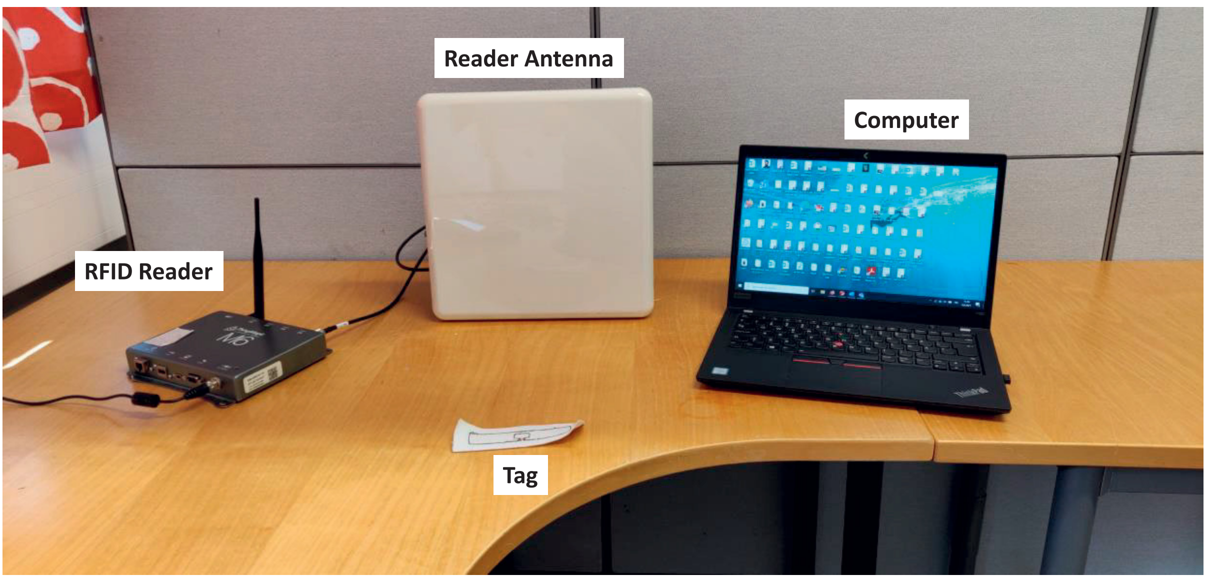

Figure 4. A real passive UHF RFID operating system in an office.

The basic concept of passive RFID technology, which has reformed logistics and supply chain management, is that the unique ID of each RFID tag can be used to wirelessly identify and track objects where the RFID tags are attached. Propagating electromagnetic waves in the UHF frequency range, used to power and communicate with the passive tags, enables the rapid interrogation of several tags through various materials. The global operating UHF RFID frequency ranges have been approved and assigned to different countries according to their regulations [157]. Table 3 presents different center frequencies approved for UHF RFID devices in different regions. Thanks to the energy-efficient mechanism of digitally modulated signal backscattering utilized in the tag-to-reader wireless communication, the tags can be read from distances of several meters.

Table 3. Operating frequency ranges of UHF RFID systems in different regions

Regions / countries	Operating frequency band (MHz)
Canada, USA	902–928
China	920.5–924.5
Europe	865.6–867.6
Japan	916.7–920.9

Adding sensing capabilities to passive RFID tags has also been widely studied and several excellent results have been achieved [158] [159] [160] [161] [162] [163]. Further, by tracking changes in the tags' backscattered signals, passive UHF RFID tags can be used for sensing without external sensors or any additional on-board electronics [164]. Especially passive UHF RFID tag-based strain sensors [165] [166] [167] [168] [169] and moisture sensors [170] [171] [172] [173] [174] have been widely studied.

Variations of backscattered signal strengths and phases from passive RFID tags attached to the human body have been shown to provide information about the movement of limbs or torso. Previously published results about body positions [175], kinematics of the leg during walking [176] [177], and classification of periodic movements and recognition of single gestures [76] have been presented with passive RFID tags attached to the body by using fixed reader antenna tag setups. Further, free-weight exercise monitoring has been done with attached RFID tags [178], RFID tags attached to the finger have been used to detect hand placement [179], and the angles of joints on the body have been tracked with multi-antenna arrays composed of RFID tags [180]. Finally, [181] [182] have shown that when a user touches an RFID tag with their finger, body conductivity changes the electric impedance of the tag antenna, which manifests as a change in the backscattered signal.

The above presented passive RFID tag–based gesture tracking and sensor results are based on modifications in the tags' backscattered signal strengths and phases caused by moving the body, actually touching the tag, or by affecting the tag environment or geometry. They can be useful in many RFID reader-antennas-tags systems, in specific environments, and especially when used from one fixed direction. However, despite showing the versatile possibilities of passive RFID technology in several fields, they show that backscattered signals of passive RFID tags are noisy and unstable, and they are strongly affected by the environment and surrounding materials [164]. Further, all RFID tag–based solutions have one significant drawback: It is not possible to read RFID tags through the human body. Since people are constantly moving and turning around and the environment has different sources of interference (for example, radiofrequency waves are absorbed by liquids and reflected by metals), basic RFID tags are also unsuitable for use in human–technology interaction.

2.2.3 Fabrication methods and materials for passive UHF RFID tags

The most popular fabrication methods of passive UHF RFID tags include screen printing [183], laser cutting [184], embroidery for fabrication of wearable tags [185], 3D printing [186], and inkjet printing [187]. The choice of materials for manufacturing the RFID tags is also an important factor that impacts the performance of tags. There are different electro-textile [184], copper [188], and conductive inks [183] used in manufacturing the passive UHF RFID tags. There are also different types of electro-textile materials: silver-based stretchable electro-textile Less EMF stretch conductive fabric (Cat. #A321) [189], non-stretchable electro-textile, nickel-plated Less EMF Shieldit super fabric (Cat. #A1220) [190], and pure copper polyester fabric [189]. These fabrics are conductive and light, and antennas could be fabricated from these fabrics and integrated into simple fabrics. The IC is a significant and basic part of any passive UHF RFID tag. The ICs are attached to antennas through different attachment methods, e.g., epoxy glue [183], printing [191], and embroidery [185] [188]. The manufacturing methods and materials used in previous studies have increased the potential of this technology to be used in human–technology interaction.

3 AIMS OF THE STUDY

The aim of this thesis is to establish human–technology interaction solutions based on clothing-integrated passive UHF RFID technology for various application fields. Novel passive UHF RFID-based clothing-integrated human–technology interaction solutions are designed; they will not rely on backscattered signal changes of passive UHF RFID tags but will instead use on/off inputs, which means that tag IDs will be turned on/off, making them readable/non-readable to the reader. Touching the cloth surface or swiping with a finger or moving arms or legs are examples of simple gestures that will be used for human–technology interaction. The already available passive UHF RFID body-centric antenna designs will be used as starting points to revolutionize the wearable applications by providing simple touch inputs. The objective and aim are to provide an efficient and reliable RFID technology and dependency on other technologies will be minimized.

The realization of proper fabrication techniques and materials are at the core of this research and critically impact the performance of the passive UHF RFID-based human–technology interaction interface. Thus, the seamless integration of RFID technology in the clothing is another major aim of this thesis study. The focus is to integrate the needed technology seamlessly and cost-effectively into daily clothing. The aim is to select suitable conductive materials, e.g., electro textiles and conductive thread for the fabrication of human–technology interactive RFID-based digital devices. The study of the materials used in fabricating the RFID platforms (antennas and interconnections) and different attachment methods of ICs will be presented in this thesis.

This thesis will introduce wireless evaluation and preliminary user testing of the designed and fabricated clothing-integrated passive UHF RFID platforms for human-technology interaction. The wireless performance of the RFID platforms will be tested in real environments so that the conclusive study can be presented for a better understanding of how this technology will work. The testing aims to include a specific designed software for this purpose and presents a variety of options for applications based on the evaluation of RFID platforms.

Finally, based on the created passive UHF RFID system designs and the established manufacturing solutions of integrating the technology into clothing, the final aim of the thesis is a proof-of-concept level launch of versatile clothing-integrated human-technology interface solutions.

The main objective of this thesis and research work is effective integration of passive UHF RFID technology into clothing for revolutionary human–technology interaction solutions. The objectives of the work are defined as:

- Design, development, and fabrication of clothing-integrated passive UHF RFID platforms for human–technology interaction. These platforms are presented in Publications (I, II, III, V)
- Wireless evaluation and preliminary user testing of clothing-integrated passive UHF RFID platforms for human–technology interaction. It has been carried out in all original publications
- Proof-of-concept level launch of clothing-integrated human–technology interaction interfaces. These results are presented in all publications

4 MATERIALS AND METHODS

This chapter introduces the materials and methods used for the fabrication of body-centric human–technology interaction systems.

4.1 Materials

This section introduces the conductive and non-conductive materials used for the manufacturing of prototypes.

4.1.1 Conductive materials

It is critical to find optimized conductive materials for the textile-integrated antennas and interconnections, in order to achieve the best possible wireless performance for the body-centric human-technology interaction systems.

4.1.1.1 Conductive thread

The thread is already used through process of embroidery in all clothing manufacturing. Therefore, it is easy to integrate the intelligence into clothing through embroidery. The conductive yarn looks like normal thread, as shown in Figure 5, and could be easily integrated into any fabric from the normal embroidery process. This conductive thread is used in the manufacturing of tag antenna and interconnecting IC pads and other conductive materials in tags. The conductive thread used in our publications is conductive multifilament-silver plated thread (Shieldex multifilament thread 110/34 dtex 2-ply HC manufactured by Shieldex statex) [189], which has a resistance of 500±100 Ω/m and a diameter of 0.16 mm. This yarn could be used for embroidered antenna fabrication or making strong connections between two conductive parts for better and stronger interconnection, as presented in Publication VII of this thesis.

Figure 5. Shieldex multifilament thread used in the research work of this thesis.

An embroidery machine is used for sewing with conductive thread in manufacturing such tag antennas. The Husqvarna Viking sewing machine (Figure 6) has been used for the embroidery. The antennas could be designed in AutoCAD software and then updated in the sewing machine. The AutoCAD is a dedicated software to draw the needed designs with smaller perfections. Then, the antenna pattern is embroidered through the sewing machine's auto function like the design in the software. This machine can embroider any shape or design, which could be loaded into the machine via a memory stick. This machine has a universal serial bus (USB) port, which could be used for data loading. This sewing machine has been used in embroidering interconnections of ICs and conductive parts of antennas, as shown in Figures 7 & 8 and Publication VII.

Figure 6. Husqvarna Viking embroidery machine.

Figure 7. Embroidered interconnections of IC and antennas.

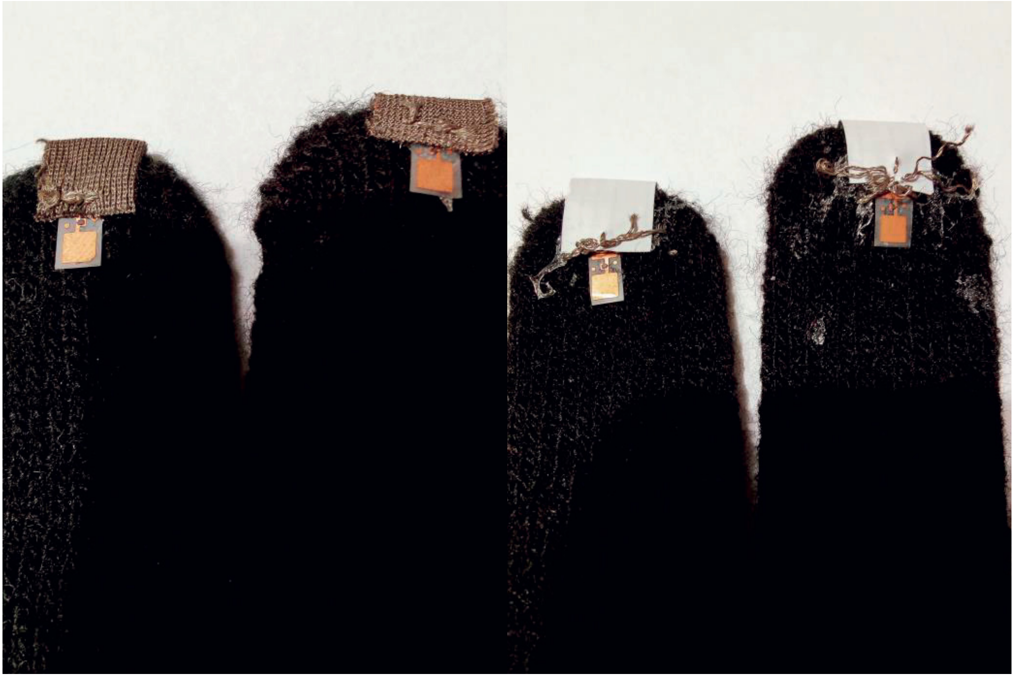

Figure 8. Embroidered interconnections of IC and antennas (closer view).

4.1.1.2 Electro-textiles (conductive fabrics)

The conductive electro-textile materials look and feel like ordinary textiles, so they are easy to integrate into normal wearable clothing. These materials are either stretchable or non-stretchable, so they easily conform to the shape of the body. Two electro-textile materials were used in this thesis, and the properties of both materials are presented in Table 4.

The first electro-textile material used in this thesis is a silver-based stretchable electro-textile Less EMF stretch conductive fabric (Cat. #A321 produced by Less EMF) [192], with a thickness of 0.4 mm and a sheet resistance of less than 1 ohm/square. This is a silver-plated knitted conductive material. According to the manufacturer, this material can be stretched to a maximum of 200%. This stretchable electro-textile is conductive from both sides, as presented in Figure 9.

This material has been used to fabricate clothing-integrated antennas to shirts and gloves by attaching the antennas with a normal textile glue. The adhesive silicone glue NuSil MED-2000 is used to attach the antenna parts to the fabrics. This glue is one part solvent-free silicone. The adhesion property is good, and it remains flexible after applying on the substrate. The highly conductive electro-textile is stretchable in both directions; the conductivity increases if stretched in one direction and decreases if stretched in the opposite direction. This material is used in the fabrication of tags in Publication II & VII.

Figure 9. Less EMF stretch conductive fabric.

The second electro-textile material used in this thesis is non-stretchable conductive, woven, and nickel-plated Less EMF Shieldit super fabric (Cat. #A1220 produced by Less EMF) [190], shown in Figure 10, which has a thickness of 0.17 mm and a sheet resistance of 0.07 ohm/square. This conductive electro-textile material has only one conductive side, and the other side is coated with non-conductive hot melt adhesive glue. This conductive material can be ironed on the clothes, and glue on the backside of the material melts and seamlessly attaches to the clothing material. This material is highly conductive and could be sewn like a normal fabric. This conductive electro-textile material has been used in Publication I, II, III, & VII for the fabrication of clothing-integrated antennas.

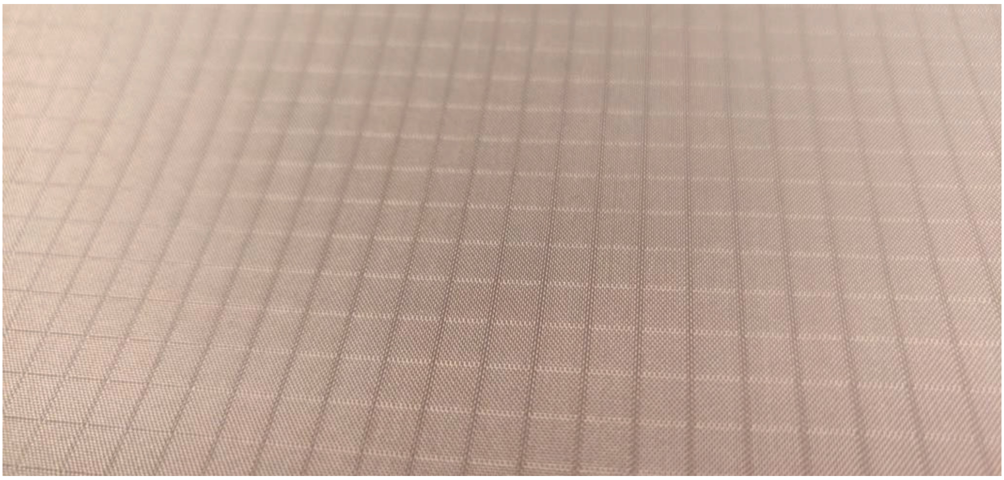

Figure 10. Less EMF Shieldit super fabric.

Table 4. Properties of two electro-textile materials used in the thesis

Material	**Commercial name**	**Properties**							
		Thickness	Weight	Resistivity	Color	Base	Conductor	Price	Stretch
Stretchable electro-textile (knitted)	Less EMF Stretch Conductive Fabric	0.40 mm	4.3 oz/yd ^{2}	<1 Ohm/square (unstretched)	Brown	76% nylon, 24% elastic fiber	Silver-plated	$ 3100 per roll (100 lin ft roll)	~100 % in length, ~65% in width
Non-stretchable electro-textile (woven)	Less EMF Shieldit Super Fabric	0.17 mm	6.784 oz/yd ^{2}	<0.07 Ohm/square	Gray	Polyester/ hot melt adhesive on the backside	Nickel- and copper-plated	$ 670 per roll (100 lin ft roll)	-

The cutting of antennas from electro-textile materials needs precision and special skill. The scissors and laser cutter have been used to cut the tag antennas in this thesis. The most advanced and precise method of cutting the antennas from conductive fabrics is a laser cutter. The Fusion Epilog Laser model 13000, shown in Figure 11, is used to make the antennas from second conductive electro-textile material. The maximum power of this laser cutter is 75 W to cut the hard materials but, in this case, the conductive fabric is soft and will burn out at this power. Just 25% of maximum power is enough to cut the conductive fabric precisely without burning out with smooth edges. The design and dimensions of antennas need to be uploaded into the computer, and the laser cutter automatically cuts the antennas accordingly. The other method of cutting the antennas is with scissors, which were used in all types of materials in this thesis. The electro-textile antennas are then integrated into cotton shirts, gloves, and other items, as shown in Figure 12.

Figure 11. Epilog laser cutter.

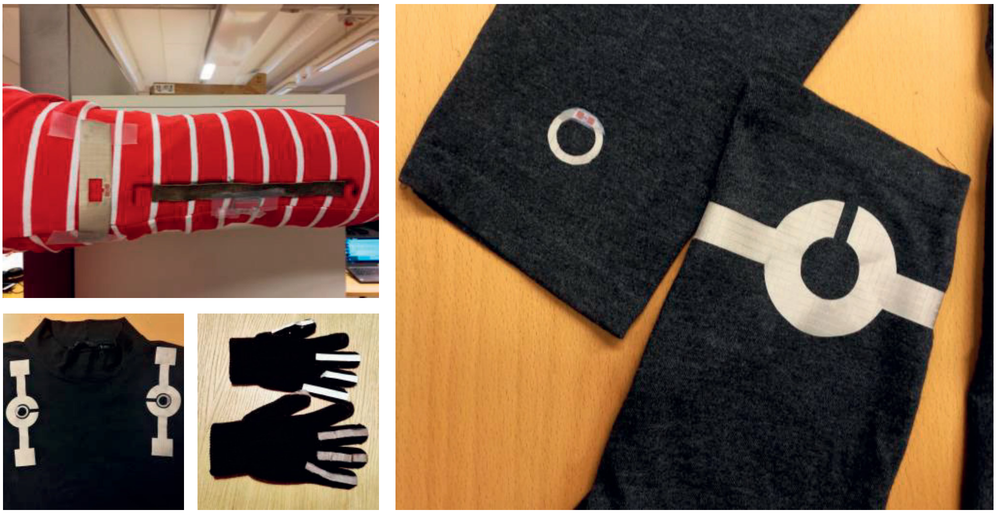

Figure 12. Conductive electro-textile materials used for fabrication of intelligent prototypes studied in the publications of this thesis.

4.1.1.3 Copper tape

The copper tape (manufactured by Holland Shielding Systems) material has excellent conductive properties with adhesive tape on the backside and could be easily applied to hard and soft surfaces. It is conductive from both sides. The copper tape has a conductivity of 58 MS/m. The color of this material is pure copper. These copper-based antennas (shown in Figure 13) are fabricated using a vinyl cutter and scissors, as in Publication I, III, IV, V, VI, & VIII.

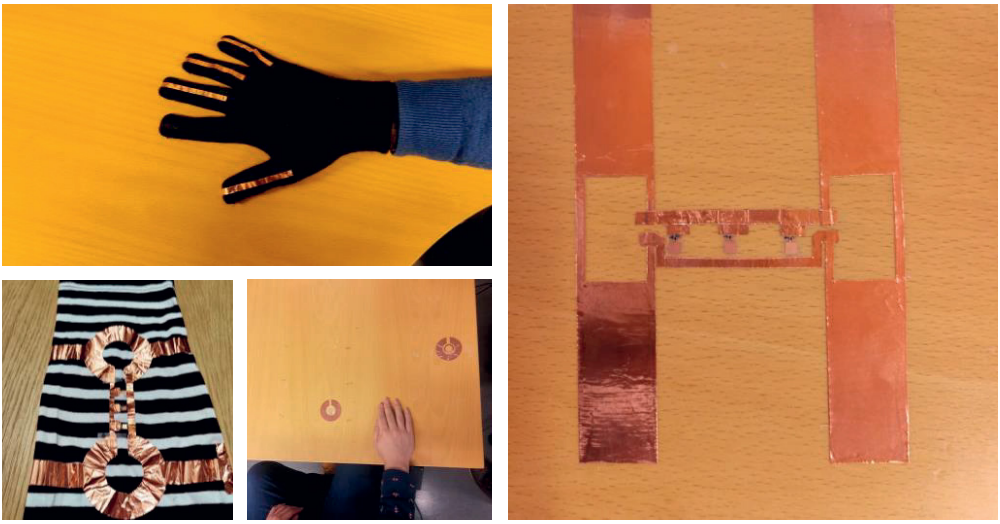

Figure 13. Copper-based body-centric human–technology interaction solutions.

The vinyl cutter, shown in Figure 14, is used to cut the antennas from copper material. This cutter has a thin blade that cuts the edges sharply and makes the small designs perfectly.

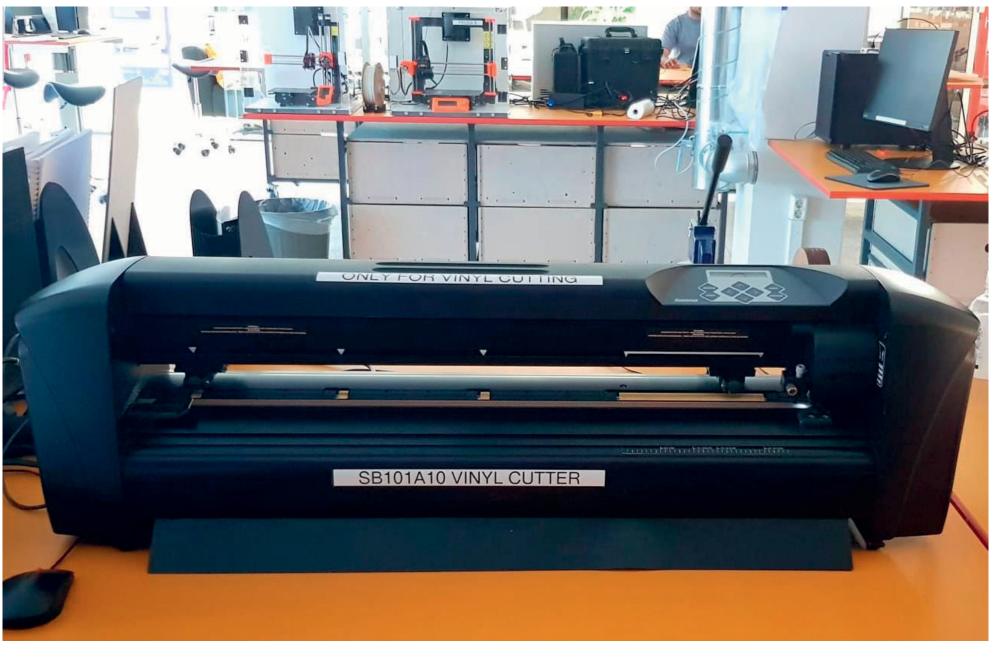

Figure 14. Vinyl cutter.

4.1.2 Non-conductive materials

Choosing the right substrate material positively impacts and efficiently contributes to the performance of clothing-integrated wireless electronics. Further, the softness and hardness of the substrate material affects the performance as well. The antennas and electronics in this thesis will be integrated into our daily clothing, which means the technology needs to adapt to the needed substrate materials.

The non-conductive materials used in this research are mostly woven and knitted cotton materials, e.g., daily clothes, such as shirts and gloves (Figure 15, Publications I, II, III, V, VI, VII, & VIII). To widen the body-centric HTI possibilities for our solutions, RFID-based human–technology interaction systems are embedded on hard surfaces in the surroundings as well, e.g., on wooden surfaces (Publications I, III, & IV).

Figure 15. Cotton-based shirt (left) and cotton glove (right).

The Ethylene-Propylene-Diene-Monomer (EPDM distributed by Goodfellow) shown in Figure 16 is 2 mm thick and has been used in Publication I. This material is non-conductive and is a great insulator between the clothing-integrated antenna and the human body.

Figure 16. EPDM material.

4.1.3 UHF RFID IC

The IC is an important part of the passive UHF RFID tags. The used IC is of NXP UCODE G2iL series RFID IC (manufactured by NXP), as shown in Figure 17. The IC comes on a plastic sheet with 3×3 mm^2 copper pads for the antenna attachment. The wakeup power of the chip is -18 dBm (15.8 µW). The thickness of the copper pads is 10 µm, the plastic film is 45 µm thick, and the total thickness of the IC is 55 µm. The copper pads are conductive and are used as connection terminals between the IC and the antenna.

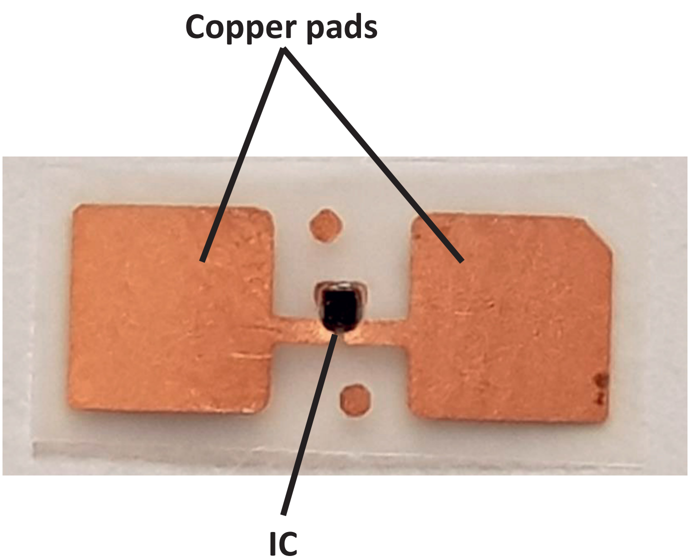

Figure 17. NXP UCODE G2iL series RFID IC that has been used in this thesis.

4.2 Wireless evaluation

4.2.1 Measurement environments

The basic wireless evaluation measurements in this research have been done in an anechoic chamber, which has excellent shielding against multipath, attenuation, interference, absorption, and reflection losses for measurements of RFID-based wireless systems. It provides a space-like environment to set a standard wireless performance scale.

The practical evaluation of the body-centric HTI solutions is done in real environments, including home, office, and hallways in all Publications. These environments have multiple interferences and deflections from surroundings due to the presence of electronic devices, furniture, people moving around, and different electrical appliances being used during the testing of body-centric human–technology interaction solutions.

4.2.2 Measurement tools

4.2.2.1 Voyantic Tagformance

A Voyantic Tagformance measurement system which includes anechoic chamber presented in Figure 18 and Voyantic Tagformance reader as shown in Figure 19. The wireless measurements and initial evaluation of the prototype performance are done using the system, which contains an RFID reader unit conducting power-frequency sweeps [191]. This system includes an anechoic chamber, an RFID reader antenna mounted inside the chamber, a Voyantic Tagformance reader, and a computer system.

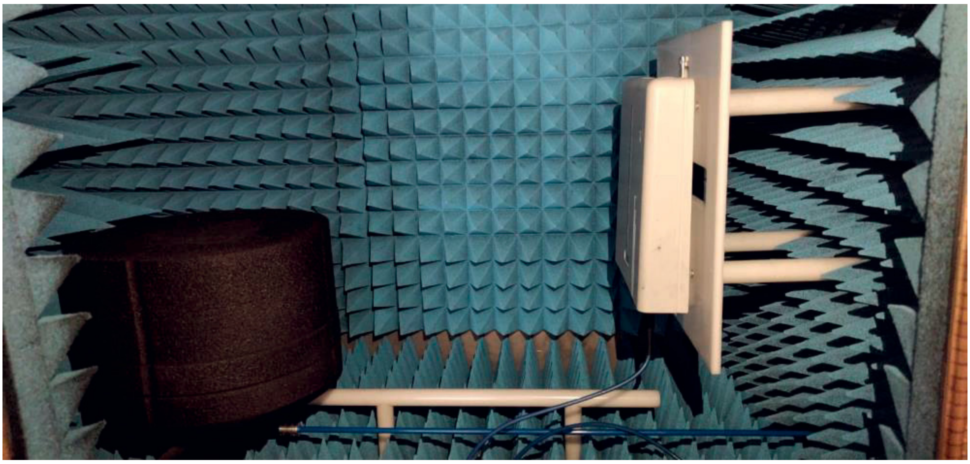

Figure 18. Anechoic chamber for Voyantic Tagformance measurement system used for initial wireless evaluation of prototypes in this thesis.

Figure 19. Voyantic Tagformance measurement system used for initial wireless evaluation of prototypes in this thesis.

The system is calibrated firstly by using a reference tag to characterize the properties of the wireless channel from the reader antenna to the tag. The achieved theoretical read range describes the maximal distance between the tag platform and the reader antenna in free space, i.e., in an environment without reflections or external disturbances. The measurement equipment calculates the theoretical read range (dTag) using the tag platform's measured threshold power and the measured forward losses, which are firstly studied using a reference tag [191], as in (1),

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}\,L_{fwd}}} \qquad (1)$$

where effective isotropic radiated power (EIRP) is the emission limit of an RFID reader, given as equivalent isotropic radiated power. In this study, *EIRP* = 3.28 W, which is the emission limit in European countries. The symbol λ is the wavelength transmitted from the reader antenna, and P_{TS} and L_{fwd} are the measured threshold power and forward losses, correspondingly [193]. The initial evaluation results of the developed body-centric human–technology interaction solutions are presented in Publication I.

4.2.2.2 Practical testing with the Mercury ThingMagic M6 reader

The practical testing has been carried out with the Mercury ThingMagic M6 RFID reader. The reader operates at the European standard frequency range (865.6–867.6 MHz) and at 28 dBm power in this study. It can read up to 750 tags per second. It can read the tags sensitivity up to -70 dBm, which is feasible for many real scenario applications in home and industrial setups. The measurement setup, which includes the platform integrated into surfaces, items, shirts, gloves, and tables, one circularly polarized RFID reader antenna attached to the ThingMagic M6 RFID reader through a connecting cable, and our testing software user interface are presented [194]. The M6 RFID reader system is presented in Figure 20. The reader and antennas are available on the market for around 1000 euros.

Figure 20. Mercury ThingMagic M6 RFID reader system used for practical testing in this thesis.

4.2.2.3 Customized software for measurements

A customized testing software has been developed for the M6 reader, and several thesis results have been gathered through this software in the publications, as the software can be customized according to the target application. The software user interface is installed in the computer. The testing software is developed on the .Net framework with C# as a Windows forms application. The testing software uses ThingMagic Mercury API tools to control the M6 reader and filters received RFID tag IDs to focus only on the ICs on the test (not to be disturbed by any surrounding RFID tags). The ThingMagic Mercury API supports continuous reading, so it was chosen to retrieve RFID tags from the M6 reader [194]. The software instructs for an input on the screen, to which the user must act accordingly, and switch off that specific tag, by covering/touching it with hand/finger. If a correct input is given by the user, a green point appears on the screen, while the software stores the input as "1" in an excel sheet. If a wrong input is given, or there is no input in 5 seconds, the software stores it as "0". The excel sheet contains the information about asked input, given input, and if the given input was correct or incorrect [195]. This software measures the backscattered signal power of an RFID tag placed at a certain distance and changes the power in real time with the movement of tag relative to the reader antenna.

4.2.2.4 Mobility through mobile RFID readers

The practical testing of the prototypes for the evaluation of applications in real-life scenarios has been done with the mobile RFID reader presented in Figure 21. The used mobile reader (Nordic ID Medea, which is designed for quick, accurate, and reliable data collection) measures the tags at 866 MHz with 27 dBm power, which is the European center frequency for UHF RFID systems, and then communicates with any background system through Wi-Fi. As the reader is handheld, and thus mobile, this user interface can be easily transferred together with the person using it [193]. Examples of testing environments and testing setups are shown in Figure 22 in Publications.

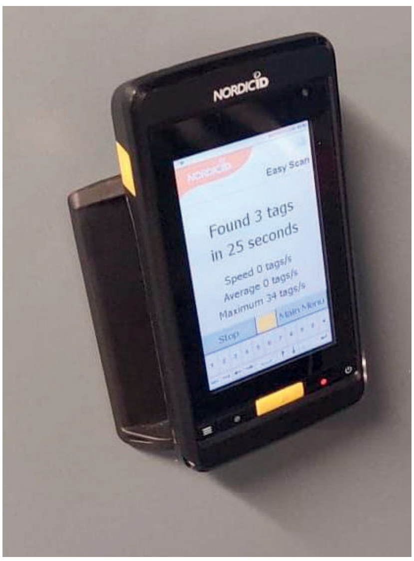

Figure 21. Nordic ID Medea mobile RFID reader.

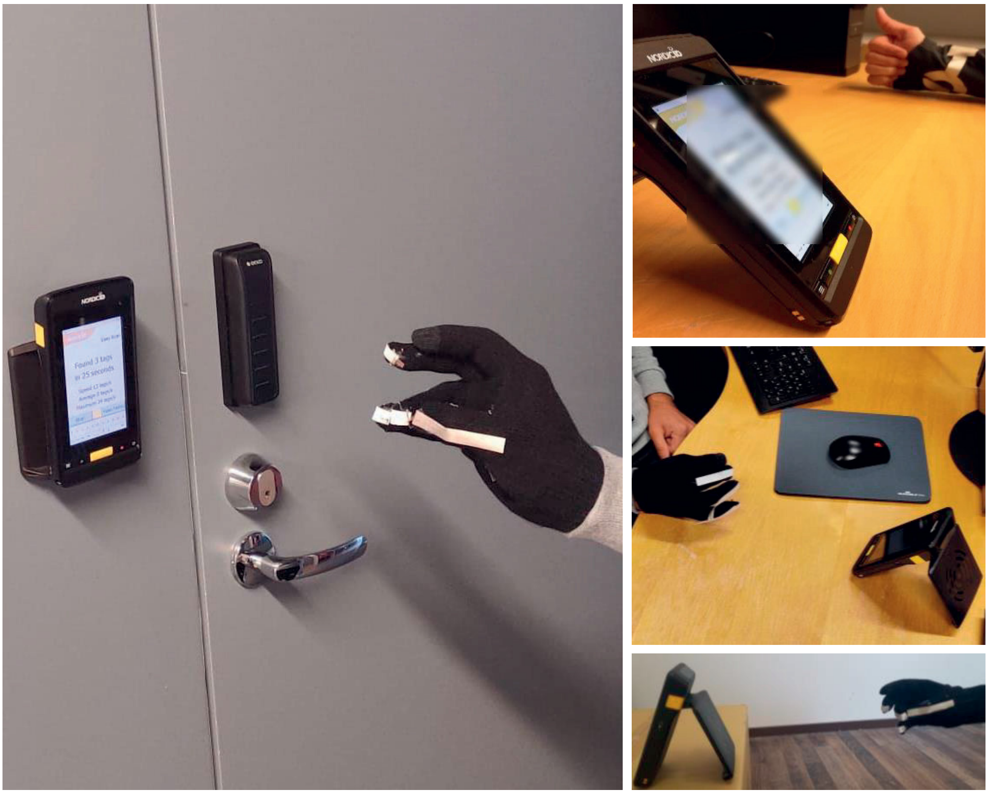

Figure 22. Testing environments and situations of developed prototypes with mobile RFID reader in different publications of this thesis.

5 SUMMARY OF RESULTS: PROOF-OF-CONCEPT LEVEL LAUNCH OF PASSIVE RFID-BASED HUMAN-TECHNOLOGY INTERACTION SOLUTIONS

As a result of the thesis work, versatile body-centric solutions designed primarily for human–technology interaction were established. The reliable read range is the main criterion to evaluate the performance of the body–centric human-technology interaction solutions in different environments. The developed solutions are categorized in three different sections: body movement–based, touch-based and finger movement–based solutions for human–technology interaction. The results of all developed solutions are presented briefly in this chapter.

5.1 Body movement–based human–technology interaction solutions

5.1.1 Wrist antennas and ID rings (Publication I)

The first prototypes of body movement–based human–technology interaction solutions fabricated from conductive electro-textile material are presented in Figure 23, [Publication I]. The antenna design used in this publication and other following studies has been previously presented in [196]. The wrist antenna is extension of the original antenna design and near-body evaluation had been presented in [196] as well in this thesis. This antenna is designed for wearable near-body applications. The performance in free space anechoic room is different than on-body and read range is significantly lower than free space, while still enough for practical implementation with a standard mobile RFID reader. This system uses centrally aligned split ring tag antennas. These tag antennas were named as wrist antennas and small rings (with attached IC) as ID rings. Different wrist antennas were fabricated from Less EMF Shieldit super fabric, and small rings were fabricated from copper tape and the same electro-textile material as shown in Figure 24. The other part of the system consists of small identification (ID) ring antennas, each with a unique ID, embedded into our environment. Each ID ring has an RFID integrated circuit (IC) and can thus be "activated" by placing the shirtsleeve next to the specific ID ring [193].

Figure 23. First body movement–based interaction solution, a wrist antenna and small ID ring integrated into the shirtsleeve [Publication I].

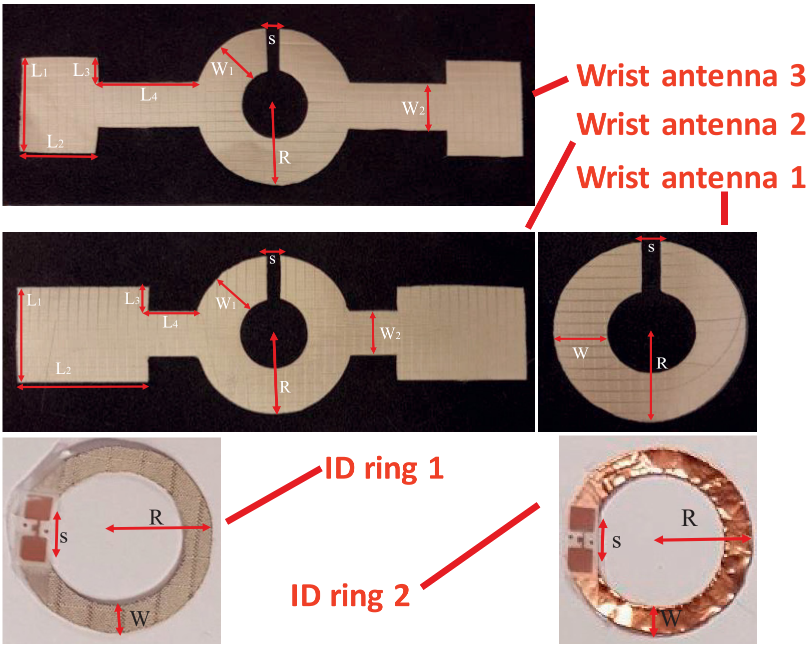

Figure 24. RFID tags (wrist/ID rings) fabricated from conductive electro-textile and copper material [Publication I].

The initial evaluation of the wireless performance of the tags was carried out with Voyantic Tagformance in an anechoic chamber, and results were compared in a graph (Figure 25). The wireless evaluation was carried out with a mobile RFID reader (Nordic ID Medea). This mobile RFID reader operates at 866 MHz. Further, the wrist antennas were compared while trying to activate the ID rings integrated on the table, item, and shirtsleeve through the Nordic ID Medea mobile RFID reader. The results are compared in Table 5. The best wrist antennas (wrist antenna 3) with higher read ranges were selected to integrate into the shirtsleeve and for further practical wireless evaluation in a real office environment, as presented in Figure 26.

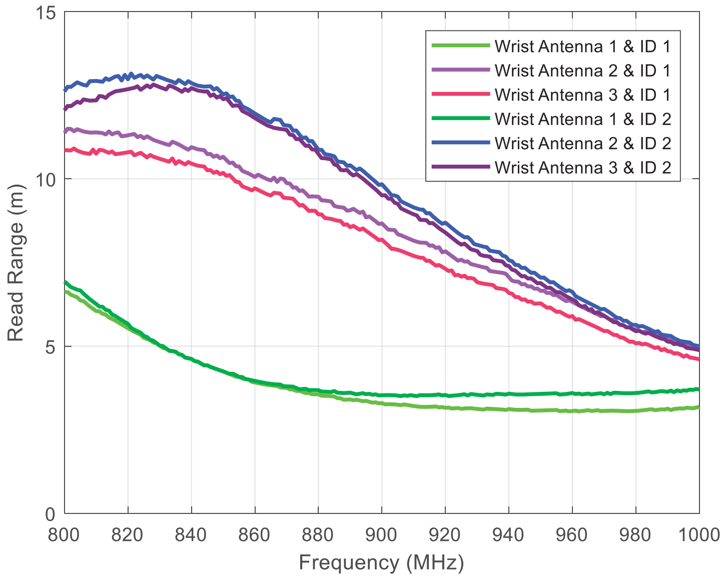

Figure 25. Initial evaluation of three different designed tags and ID rings (fabricated from electro-textile/copper tape) with Voyantic Tagformance in an anechoic room [Publication I].

Table 5. Reading distance of ID rings in different positions [Publication I]

ID 1 (Item)	ID 2 (Table)	ID 3 (Wrist)
Wrist antenna 1 44 cm	Wrist antenna 1 36 cm	Wrist antenna 1 36 cm
Wrist antenna 2 45 cm	Wrist antenna 2 38 cm	Wrist antenna 2 40 cm
Wrist antenna 3 51 cm	Wrist antenna 3 80 cm	Wrist antenna 3 56 cm

The best wrist antenna (wrist antenna 3) integrated in the shirtsleeve was used to activate the ID ring placed on the item (ID1), table (ID2), and shirtsleeve (ID3). The clothing integrated wrist antenna 3 showed excellent performance. The first prototype of this system presented, which can be used when sitting by a table, allows wireless controlling of technology by simple hand movements. The achieved read ranges are very promising, allowing activation of ID rings from distances of around 0.5–1 meters from a mobile RFID reader placed on a table [193]. A feasible distance for many practical applications is around 0.5 meters.

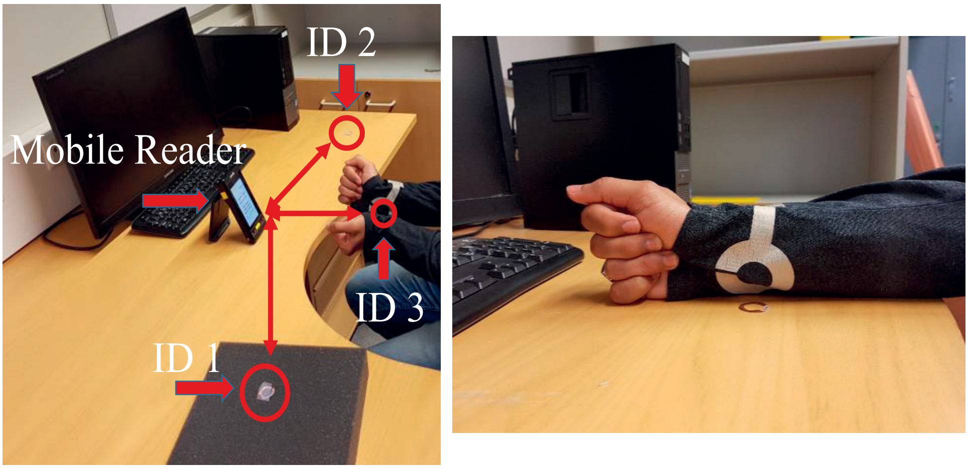

Figure 26. A tag antenna integrated into a shirt successfully used to identify the item (ID1), table (ID2), and wrist (ID3) with a mobile RFID reader in an office environment [Publication I].

5.1.2 Sleeve-integrated strain sensors (Publication II)

Another body movement–based interaction has been presented in [Publication II]. A passive UHF RFID strain sensor tag and a reference tag had been integrated on the plain cotton shirt sleeve with normal textile glue. Both sensor and reference tag had been fabricated from Less EMF stretch (stretchable) and Less EMF Shieldit super fabric (non-stretchable) conductive electro-textile materials respectively [Publication II]. The antenna design used in this publication is originally studied in [197]. The sensor tag was placed at the elbow, which responded with a changed backscattered power of signal when the elbow was bent. The bending of the elbow was a body movement that provided input in the form of backscattered power. The change in the backscattered power of signal provides enough information about the state of the body [198]. The reference tag provided a stable reference to remove the effects of the environment and reading distance. The bending scenario and integrated tags in a shirt sleeve are shown in Figure 27.

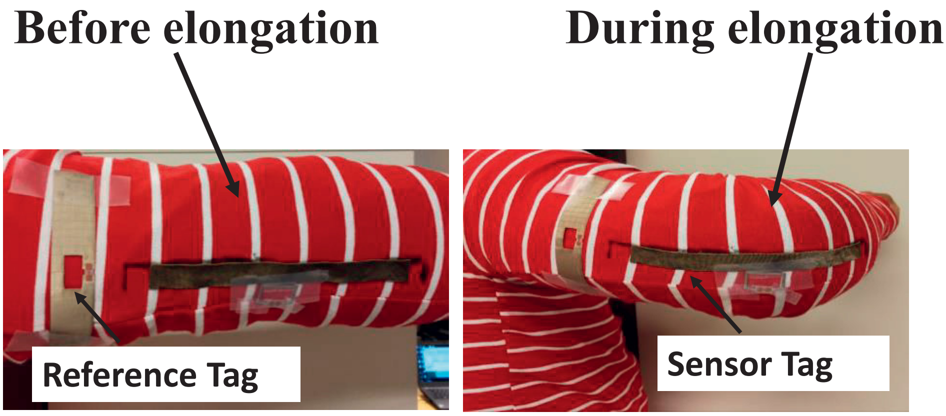

Figure 27. A sensor and reference tag integrated in the shirt sleeve with straight (left) and bent elbow (right) [Publication II].

The platform was tested on both arms in an office environment (Figure 28) and achieved a working read range of 1 meter, which was considered suitable for the first prototype. The percentage variation of backscattered power ΔP % from the reference tag to the sensor tag enabled us to decide about the state of the arm at different angles (with changing backscatter power due to stretching of the elbow) and backscattered power evaluation is shown in Table 6 for different distances. As shown in Figure 29 (both home/office environment) on a male subject, the graphs showed significant changes in the numerical value of ΔP % when the elbow was bent or stretched more than 45°, and hence it could be concluded that the change in backscattered power through body movement gives significant information about the position of the respective body part. The change was evident in 0–90° arm movement from the variation of backscatter power. The difference between the platform's final (during elongation) and initial value (before elongation) was more than 0.10 for both arms [199]. This 0.1 corresponds to a variation of 10%, which corresponds to a 17–20 dB change in the backscattered power in an office environment, while in a home environment, it corresponds to around 10–12 dB change in the backscattered power [199]. Thus, it is possible to record human arm movement with these shirt-integrated simple and passive RFID components. Our developed sensor user interface provides an interesting option for human-technology interaction [199]. It has a wide range of applications from smart housing to environmental controlling and communication.

Table 6. Reading distance and backscattered power in an office environment [Publication II]

Read Range/Left arm	**70 cm**	**80 cm**	**90 cm**	**100 cm**
Straight	-66 dBm	-68 dBm	-70 dBm	-71 dBm
Bent ≥ 30°	-70 dBm	-70 dBm	-71 dBm	-71 dBm
Read Range/Right arm	**70 cm**	**80 cm**	**90 cm**	**100 cm**
Straight	-67 dBm	-69 dBm	-70 dBm	-71 dBm
Bent ≥ 30°	-68 dBm	-70 dBm	-71 dBm	-71 dBm

Figure 28. The measurement setup of a body movement–based sensor in an office environment, bent (top), and straight elbow (bottom) [Publication II].

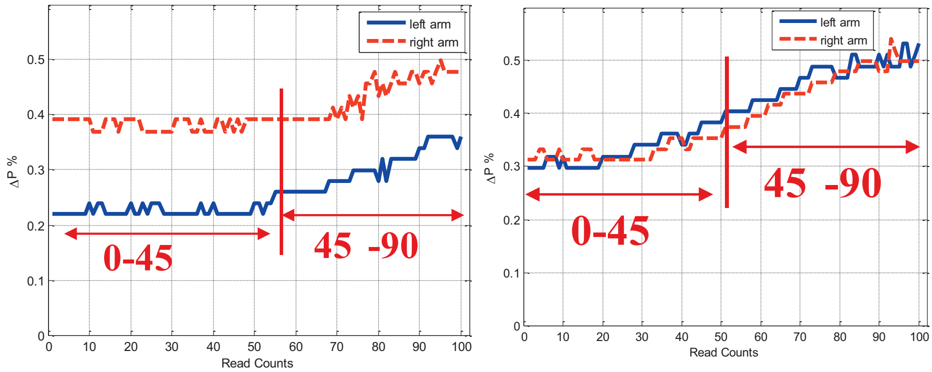

Figure 29. The change in ΔP % value of platform tested in an office environment (left) and home environment (right) on a male subject [Publication II].

5.2 Touch-based human–technology interaction solutions (Publication III)

The next phase of our research work was touch-based human–technology interaction solutions. Specific Item, Body, and Table RFID tags were created, as presented in Figure 30. The item, body, and table tags are passive UHF RFID tags which are attached to item, body, and table respectively. Here, two types of RFID tags fabricated from copper tape and Less EMF Shieldit super fabric (non-stretchable) conductive electro-textile materials had been integrated into the item, table, and shirt respectively [Publication III]. All the integrated tags were initially readable by an RFID reader, as shown from the gathered backscattered powers in Table 7, for the created body and table test setups. The distance between the reader antenna and the integrated Body/Item tags was 1 meter, while for the table test the distance was 70 cm. It is clear from Table 7 that distance has a significant role in the decreased backscattered signal power, but the human body also decreased the performance of the tags in the body test. In the body test, the user is wearing the shirt and standing close to the Item tag as well, but in the table test the user is sitting and the tags are not close to the tester's body. These measurement setups in an office environment with the platform and M6 RFID reader system are shown in Figure 31.

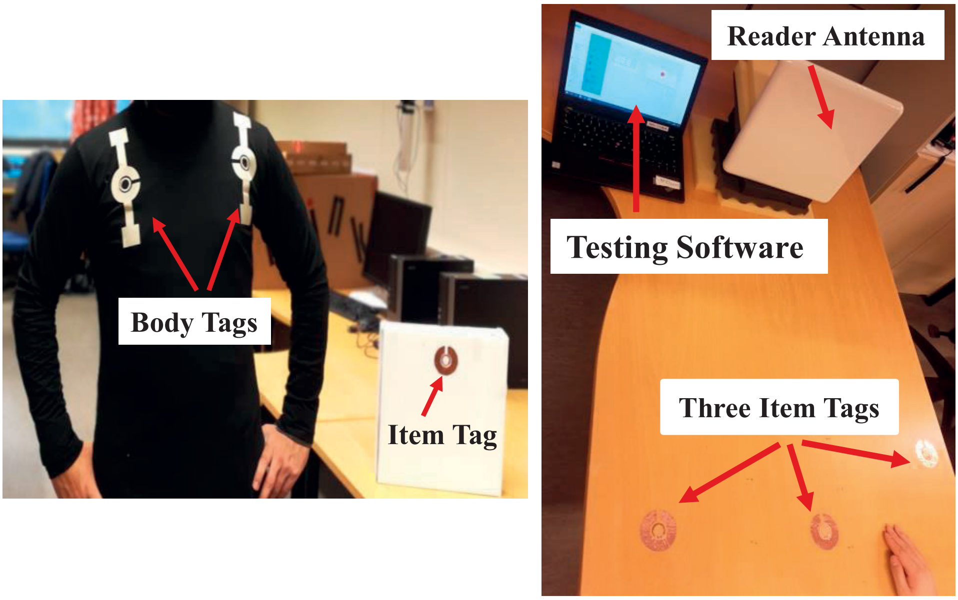

Figure 30. RFID tags integrated into the shirt/item (left) and table (right) [Publication III].

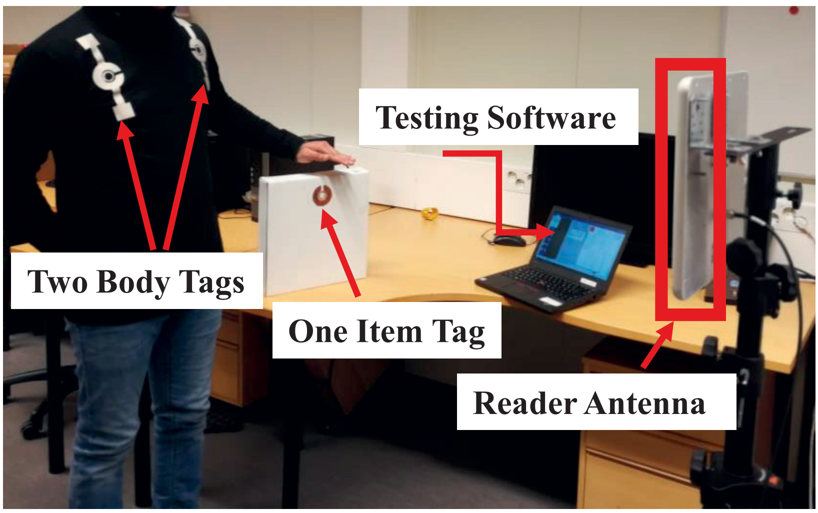

Figure 31. The measurement setup included shirt and item in an office environment [Publication III].

The all-time readable tag can be "switched off" by covering the tag with the hand, which manifested a digital input to any connected device. Success rates of 99–100% and 94–98% were achieved in the body and table tests, respectively, when two people tested the solution [Publication III].

Table 7. Backscattered power of the tags integrated on body, item, and table [Publication III]

Tester	Body test			Table test		
	Body (left)	**Body** (right)	**Item**	**Left**	**Middle**	**Right**
U1	-55 dBm	-56 dBm	-54 dBm	-46 dBm	-42 dBm	-49 dBm
U2	-54 dBm	-53 dBm	-56 dBm	-47 dBm	-42 dBm	-49 dBm

5.3 Finger movement–based human–technology interaction solutions

5.3.1 Finger movement–based platforms on table and sleeve (Publication IV, V)

The first finger movement–based human–technology interaction solution was fabricated from copper tape, and it comprised of two dipole antennas and three ICs. The first version was fixed to the surface of a wooden table as shown in Figure 32 [Publication IV]. This typical dipole antenna has been studied previously in [200], it is specifically designed for near-body applications. The integrated ICs were activated by a gentle finger touch and provided desired digital input into the computer. The table–based platform thus provided three separate inputs (button 1, button 2, button 3) and swiping (left/right) options. The platform was tested in an office environment, as shown in Figure 33. The preliminary testing of the platform was carried out by two users with 200 random inputs, and they achieved 98–99% success rates, as presented in [Publication IV]. The excellent results were found encouraging for versatile application possibilities.

Figure 32. Finger movement–based human–technology interaction platform (IC copper pads and antennas facing apart) to the surface of a wooden table [Publication IV].

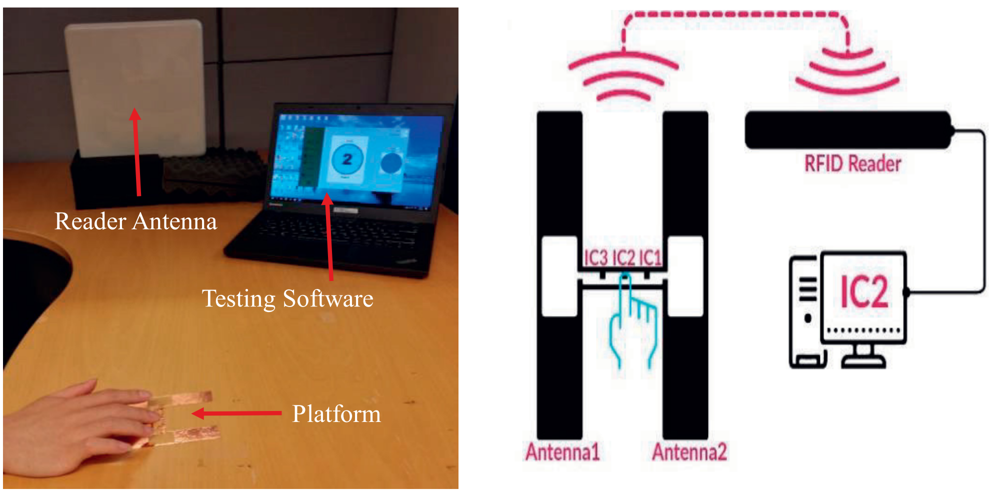

Figure 33. The platform testing setup in an office environment (left) and working principle of the platform on a table (right) [Publication IV].

Next, the finger movement–based human–technology interaction solution fabricated from copper tape material was integrated into the shirt sleeve. The working capability of this platform from different directions has been studied in detail in Publication [V]. The platform has a read range of 70-80 cm from all four directions and backscattered power of -43 to -56 dBm. It is evident that platform has good performance in from directions. The prototype working mechanism is shown in Figure 34. The principle is similar to the platform integrated into a table: Three ICs act as separate inputs and can be activated by simple gentle finger touch. Also, this platform provided three separate inputs (button 1, button 2, button 3) and swiping (left/right) options. The platform was placed on the table and tested and was then worn by the users and tested while standing in front of the reader antenna. The platform was tested by seven users in an office environment (Figure 35).

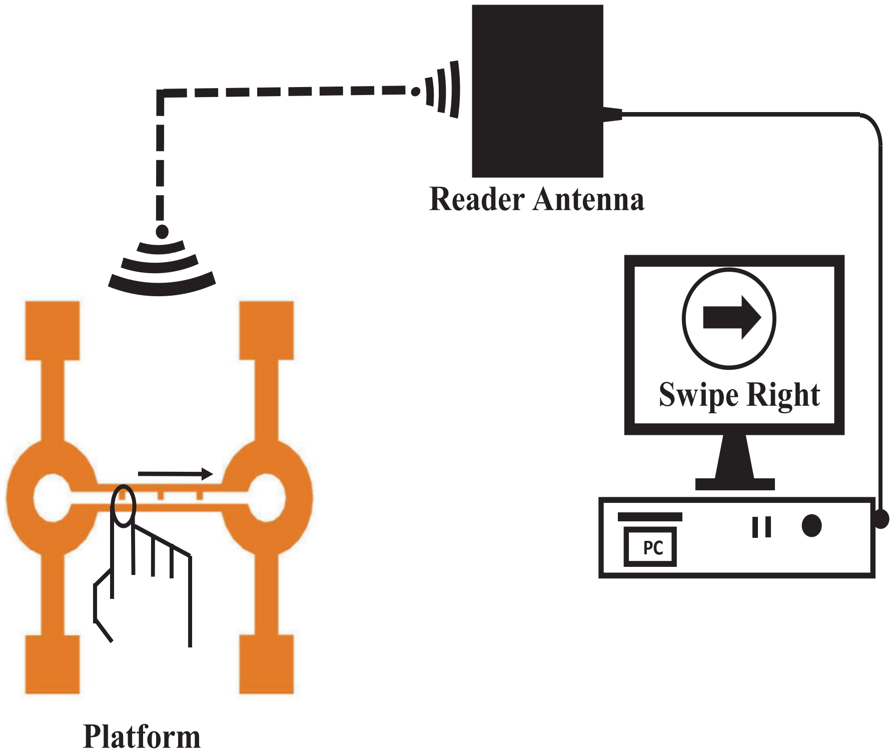

Figure 34. The working principle of a platform on a sleeve [Publication V].

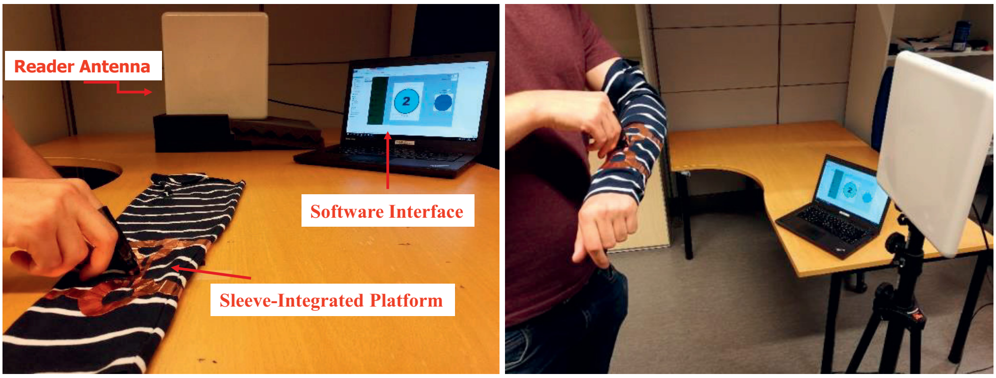

Figure 35. The platform testing on a table (left) and standing in front of a reader antenna (right) [Publication V].

5.3.2 Finger movement–based platforms on gloves (Publication VI, VII, VIII)

Finally, finger movement–based platforms on cotton-based gloves were created using passive UHF RFID tags fabricated from copper tape, as shown in Figure 36. The antenna design has been previously studied and presented in [201]. The user interface on the glove consists of three antenna parts on three different fingers of the glove, each of which has an RFID microchip with a unique ID. Further, an additional antenna part is attached to the thumb of the glove. The antennas are initially separated from each other, and none of the microchips is readable for the RFID reader. When the thumb antenna touches any of the three finger antennas, the touch creates an electrical connection, and the corresponding microchip can be detected by the RFID reader [202]. The gloves are quite thick, which creates a space between the antennas and body and reduces the impact of human body on the performance of the antennas. Further, when the glove is operated by the user, it is relatively far from the body. Thus, human body has a minimal effect on the performance of the platforms.

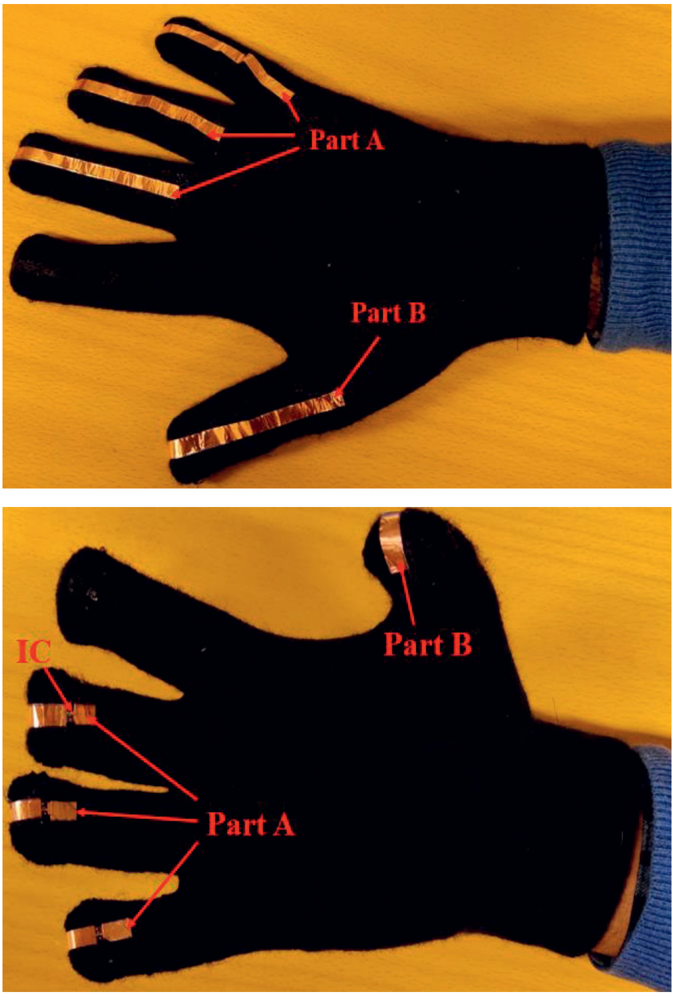

Figure 36. The top side of the glove (top) and bottom side of the glove (bottom) [Publication VI].

These first glove prototypes were tested in an office environment, as shown in Figure 37. The platform was tested with a game-like software by three people. The 1, 2, 3 inputs and swipe right/left were tested by three other users. The average success rate of this solution was 98%.

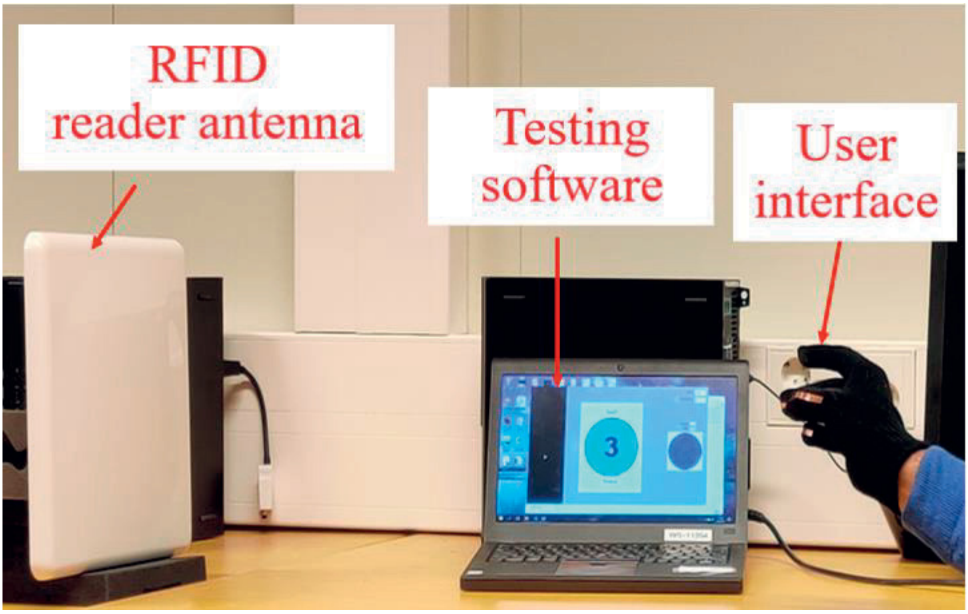

Figure 37. The glove platform being tested in an office environment [Publication VI].

Next, the glove-integrated antennas were fabricated from two different materials: Less EMF stretch (stretchable) and Less EMF Shieldit super fabric (non-stretchable) conductive electro-textile materials. An example platform is presented in Figure 38. The antennas were attached into the fingers of the same cotton-based gloves with glue, and ICs were attached with conductive silver epoxy and embroidery (conductive thread).

These finger movement–based human–technology interaction solutions were tested by six people in home and office environments with an M6 RFID reader and mobile RFID reader, as shown in Figure 39. The platforms achieved an overall 93–100% success rate. Especially the platforms manufactured from Less EMF Shieldit super fabric non-stretchable conductive textile material and antenna–IC interconnections embroidered with conductive thread showed excellent wireless performance. The gloves also show reliable functionality when tested with a mobile reader in practical identification and access control application, as presented in Figure 39.

Figure 38. The glove platform fabricated from non-stretchable conductive textile material [Publication VII].

Figure 39. The glove platform tested in a home environment (left) and an office environment (right) with mobile and M6 RFID readers [Publication VII].

Finally, the finger movement–based human–technology interaction solution fabricated from copper tape was extended for an alternative and assistive communication (AAC) solution, as presented in [Publication VIII] and shown in Figure 40. Each IC had a unique ID and could activate a specific message, as presented in Figure 41, which could be shown on a computer screen. The glove was tested in an office environment with an M6 RFID reader, as shown in Figure 42. It was tested by two users, and a 100% success rate was achieved.

Figure 40. AAC gloves tested in a home environment (left) and an office environment (right) with mobile and M6 RFID readers [Publication VIII].

Figure 41. Messages corresponding to respective ICs in the middle finger (top left), ring finger (bottom left), and small finger (right) [Publication VIII].

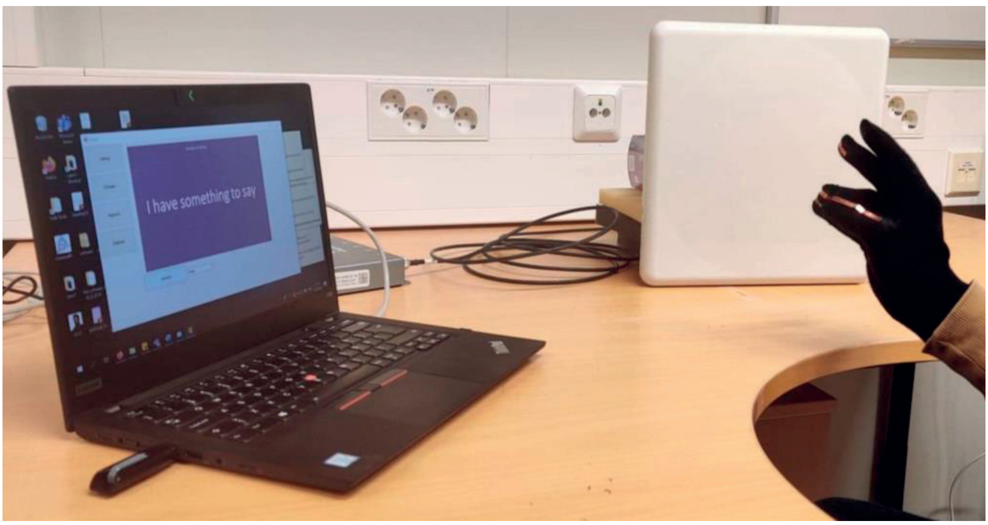

Figure 42. Testing environment of AAC gloves with an M6 RFID reader in an office environment [Publication VIII].

6 DISCUSSION

Passive UHF RFID technology has come a long way from its initial tracking and identification purposes [203] [204] through fixed readers. Based on the achieved results, the developed clothing-integrated passive UHF RFID solution prototypes provide potential for easily available and individually tailored human-technology interaction garments. Unlike other technologies, which require on-cloth energy sources and complex electronics [34] [38] [39], these solutions are light, cost-effective, and maintenance-free. Reliable and simple solutions can be provided by using RFID in a way that does not rely on backscattered signal changes, like the previous solutions [75] [205] [77], but instead uses on/off inputs, which means that IC IDs will be turned on/off, making them readable/non-readable to the reader.

Electro-textiles and embroidery with conductive thread are well-studied manufacturing methods of textile electronics [206] [207] [208], and also now found suitable options when manufacturing and materials for such garments are considered. As the developed prototypes were evaluated with a mobile reader as well, it can be concluded that the created technology provides suitable mobility for practical applications of body-centric communication. This reflects back to the initial applications of passive UHF RFID technology, tracking of items with handheld readers [209]. Further, with the possibility of our mobile phones to read the UHF RFID platforms, the application possibilities are endless.

The measurements of all the designed RFID platforms were carried out in an office environment, while Publications (II) and (VII) studied the performance in a home environment as well. Human body contains complex tissues, and when antennas work near the human body, the radiation pattern becomes distorted, and performance of antennas greatly reduced [210] [211]. Mostly the measurements were carried out by male subjects. However, in some critical RFID systems, the measurements were carried out by female subjects as well. The measurements by female subjects were carried out in Publications (II, V, VI, VII) and the purpose was to confirm the performance on different human bodies. The gathered results proved that mainly the environment affected the performance of the systems. The home environment incurred more losses to the wireless system and the performance was a little less than in the office environment. However, the success rate remained above 95 % in all of the tests.

The possibilities of these maintenance-free human-technology interaction garments in AAC, teaching and learning, as well as in the entertainment sector, for example in game controllers, are interesting future aspects to study. The developed user interface has various application possibilities especially for special needs users. For patients with physical inabilities in hands, such as spasticity or muscle weakness, the solution enables game controlling without a need of holding a controller. It provides also alternative controlling method for patients with challenges in controlling precise movements (for example due tremor) or for people who have challenges in producing voice. Both mentioned symptoms occur for example in Parkinson's disease [193]. The mentioned on-body user interface-controlled games could also be targeted for neurological patients for rehabilitation. To name an example, spatial neglect (a failure to report, respond, or orient to stimuli in contralesional space after a brain injury that is not explained by primary sensory or motor deficits) rehabilitation could benefit from a game in which the player must become aware of the affected side by touching it with the healthy side [193] [212]. The system presented is cost effective, maintenance free, and passive, which could be seamlessly integrated into different types of apparels and other surroundings for easy interaction. Further, with the possibility of mobile phones to read the UHF RFID platforms the access to versatile applications would become easy. This will make it possible to develop and facilitate various body parts, movements, and touches into physical and digital inputs. However, the achieved results are preliminary, achieved only in a few scenarios, and tested by only a few people. The next steps of research thus include further antenna optimization (considering the versatile movements of the human body and focusing on longer read ranges), as well as testing of the next prototypes in different environments and by a bigger number of testers.

7 CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

Currently the options for screen-based human-technology interfaces are usually voice- or body movement-based. Voice-controlled interfaces have their own challenges, such as linguistic coverage, and challenges in noisy environments and places that require silence. There is an urgent need for a human-technology interface that allows simple and instinctive input actions into different applications.

In this thesis, passive UHF RFID–technology is used in a new way, as a body movement-based solution for human-technology interaction. Clothing-integrated passive UHF RFID technology uses battery-free remotely addressable electronic tags composed only of an antenna and a small IC. This thesis concluded with several RFID-based interface solutions (sleeve, glove) multiple types of inputs (swipe, touch, finger movement, hand movement) through RFID platforms, and controlling the surrounding and communicating with RFID-based on/off functions. The created prototypes showed reliable functionality also when tested with a mobile reader. The first practical applications in identification, communication, game, and access control fields were found promising.

Thus, these first results are very encouraging, particularly when considering that the body centric integrated user interfaces, being a seamless part of the garment and functional without batteries, promise versatile applications for assistive technology, for entertainment, and ambient assistant living, and for comfort and safety in work environments, just to name a few examples. All the presented wearable interfaces are manufactured successfully from cost-effective electro-textile, copper tape, or conductive thread materials. Further, the integrated ICs cost only a few cents and each created solution consists of only 1-3 ICs.

7.2 Future work

The Passive UHF RFID technology has emerged as a recent passive technology for information processing and transferring. The identification of items and objects has been a key property of this technology, but with the increasing interest in passive technologies, the role of RFID has become more vital in challenging old technologies. The work in this thesis has opened the door for the technology to be used in a new way as a clothing-integrated human–technology interaction solution. With the help of passive UHF RFID, simple body movements and gestures can be used as inputs to the digital world around us. The thesis has opened the door for interesting new research directions, which will be discussed in this chapter. However, there is also room for technical improvements, and these ideas will be presented in the chapter as well.

Firstly, the work done in this thesis has opened an interesting new research direction that holds high scientific, technical, and societal impact potential. The currently available assisting technologies, such as tablets and specific devices, are not enough to overcome the versatile communication and participation restrictions of people with disabilities. For example, conditions like cerebral palsy, motor neuron disease, multiple sclerosis, and Parkinson's disease cause motor speech disorders and disabilities in fine motor skills (e.g., writing, using devices). The current assistive technologies are too cumbersome to use in everyday life, often bulky, and their use requires motor and/or cognitive skills and, often, another person's help. Most of all, they require frequent maintenance, such as charging the battery. Thus, for future research, the developed clothing-integrated technology will be transferred to the field of assistive technology.

Secondly, although the RFID-based technologies in this thesis have been limited to certain parts of the body, mostly as shirts and gloves, the RFID platform could be placed on any part of the body, and that part itself could be used for interaction and controlling the environment. For example, it will be interesting to integrate such solutions to shoes and hats. The RFID-based interfaces (antennas, ICs) are visible in the prototypes of this thesis, and these could be made invisible by seamlessly integrating them in future studies. Further, the antennas can be designed to enhance the aesthetics and fashionability of clothing-integrated user interfaces. An interesting future direction is collaboration of RFID technology and fashion design.

Finally, the entertainment sector has flourished significantly with the advancement of technology. All the latest digital devices are designed to increase users' interest in the product and engage them for a longer period. Gaming devices such as PlayStation and Xbox have attracted all age groups. In addition to adding a fun new aspect to gaming, integrating the game controller into our daily clothing will be especially useful for serious games, such as those used for activation and rehabilitation. Further, with this technology, we can provide controllers for different devices of the home, including home entertainment theaters, lights, and doors.

Regarding the next technical steps, the main goal is to improve the overall wireless performance and practical use possibilities of the clothing-integrated solutions. In this thesis, all the wireless testing was done by one user at a time. Important next steps are to start testing the clothing-integrated systems in multiuser situations and create testing setups with multiple reader antennas in order to create a system that is functional in the room from all directions. Though the platform layouts are big in terms of user experience, these are initial studies, which provide the base for clothing-integrated, passive RFID-based human-technology interaction. But still, the test users were comfortable to use the developed prototypes and to implement these in real scenarios. In the future, the technology is aimed to be minimized for better comfortability. Additionally, the RFID microchip used in making the tag antennas belongs to NXP UCODE G2iL, with a wake-up power of −18dBm, 15.8 µW, which is a second-generation series IC of this family. Currently, there are UCODE 8/8m series RFID microchip series with a −22.9dBm read sensitivity [213], which should provide higher performance and efficiency than the second-generation series.

Further, as described, the developed human–technology interaction clothes can be powered and connected by external RFID readers and interrogated through Wi-Fi, which is an optimal solution in home and school environments, care homes, and healthcare institutes. When a person is walking and away from home, this intelligent clothing could be powered directly by an RFID reader in one's mobile phone, which will make the system truly mobile. The development of such a system is currently ongoing but establishing such a fully mobile solution still requires designing and optimizing new types of clothing-integrated antenna systems, which are also important technical next steps of this work.

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PUBLICATIONS

PUBLICATION I

Clothing-Integrated RFID-based Interface for Human-technology Interaction

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***Abstract*—In this paper, we present a new type of passive ultra-high frequency (UHF) radio frequency identification (RFID)-based user interface for human-technology interaction. Our system is controlled with a shirtsleeve-integrated electro-textile antenna. The other part of the system consists of small identification (ID) ring antennas, each with a unique ID, embedded into our environment. Each ID ring has an RFID integrated circuit (IC) and can thus be "activated" by placing the shirtsleeve next to the specific ID ring. The shirtsleeve-integrated antenna has bands going around the wrist, thus increasing the read range even when the ring is behind the wrist. This cost-effective and maintenance-free solution can be seamlessly integrated into our everyday clothing, as well as into furniture, textiles, and items around us. The presented first prototype of this system, which can be used when sitting by a table, allows wireless controlling of technology by simple hand movements. The achieved read ranges are very promising, allowing activation of ID rings from distances of around 0.5-1 meters from a mobile RFID reader placed on a table.**

Keywords*—*human-computer interaction, natural user interface, passive UHF RFID, textile electronics.

I. Introduction

Interaction with technology has become extremely important in our daily lives. Due to versatile use environments and disabilities of people, current handheld, screen-based and touch- or voice-operated devices are not suitable for all consumers and all situations [1]-[3]. Currently touchless human-technology interfaces are usually voice- or body movement -based. Voice-controlled interfaces have their own challenges, such as linguistic coverage, conceptual failures, challenges in noisy environments, and un-usefulness in places that require silence. Although there is a lot of research going on around the topic, and there already are notable commercial interfaces using human body movement, the available technology solutions have some drawbacks. The current solutions require a line-of-sight, which means the person needs to be directly seen by the device, or complex electronics with an on-board power source, which makes them costly and inconvenient for daily use.

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Thus, there is an urgent need for a human-technology interface, where the required input actions are touchless, simple and instinctive, allowing the whole society to effortlessly interact with the surrounding wireless world. To revolutionize our lifestyle, clothing-integrated and body-movement-based interfaces are an extremely convenient solution. In order to be truly useful in everyday life, clothing-integrated human-technology communication needs to be functional without line-of-sight, passive, and maintenance free. Functionality must be unobtrusively integrated into everyday clothing, which means the technology needs to act invisible and be cost-effective to fabricate.

In this paper, passive UHF (ultra-high frequency) RFID (radio frequency identification) –technology is used in a new way, as a body movement-based solution for human-technology interaction. Clothing-integrated passive RFID technology uses battery-free wirelessly addressable electronic tags composed only of an antenna and a small integrated circuit (IC). As it uses propagating electromagnetic waves in the UHF frequency range, this technology enables rapid interrogation of several RFID tags. Thanks to the energy-efficient mechanism of digitally modulated signal backscattering, utilized in the wireless communication, tags can be read from distances of several meters, even through various materials.

Variations of backscattered signal strengths and phases from on-body passive RFID tags have been shown to successfully provide information about body positions and movements, for example in [4]-[7]. However, the backscattered signals of passive RFID tags are noisy and unstable, and strongly affected by the environment, which is a major challenge when implementing the presented solutions into practical use in our everyday environments.

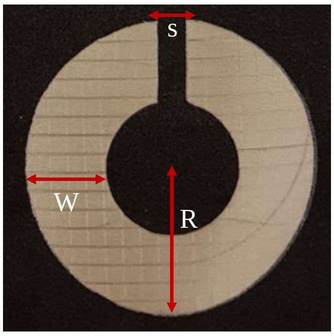
Our clothing-integrated solution for human-technology interaction has two novel features: reliable and natural on/off activation of inputs by simple hand movements and functionality even when the line-of-sight is blocked by the body. Our clothing-integrated system consists of centrally aligned split ring tag antennas, attached on shirtsleeves with antenna bands that go around the wrist. These split ring antenna tags, such as the ones presented in [8][9], enable two-layer structures. In one layer, we have a series of small ring antennas, each with own IC and ID, integrated into different parts of our clothing or into furniture, items, and textiles around us. In the other layer, a bigger ring, which will act as a radiating antenna, can be integrated, e.g., into a wrist of a shirt. Then, by taking the wrist with the bigger ring next to the desired ID ring, the tag will be "activated" and its ID will be read by an RFID reader. As only the tag ID is read and the ID codes a specific action, this system is more reliable compared to solutions based on measuring noisy backscattered signal strength or phase. The other novel feature in the system is the modification of the bigger ring to include separate radiating elements that go around the wrist. This way we can circumvent possibly blocking body and the read range is increased substantially.

As the RFID reader can be connected to any application through wireless fidelity (WIFI), these split ring tags will work as wireless input points on body, furniture, and items. By activating a specific ID, an explicit wireless input can be given to any connected device, which will allow a person to interact with the digital environment through clothes. Thus, in our approach, reading the ID of a specific IC is used as shortcuts to desired digital actions, allowing all connected devices to be controlled accurately but effortlessly, which will offer a new level of convenience.

II. Antenna Designs and Antenna Fabrication

A. Antenna Designs

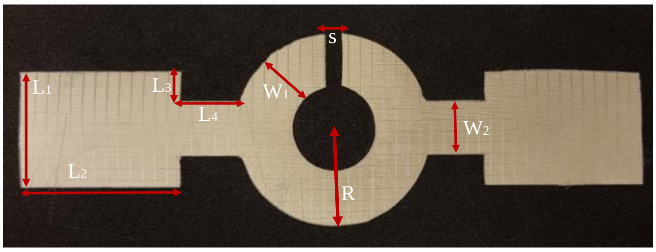
Firstly, we implemented three different types of wrist antennas in order to find an optimal solution to be used to activate the ID rings. The first wrist antenna (presented in Fig. 1) was based on a previously published design [9] and consisted only of a simple ring. While this design is attractive due to its simplicity, the human wrist will cover the whole tag during actual use, which will most probably affect the wireless performance of this antenna design and decrease the read range.



Width (W)	*18 mm*
Radius (R)	*30 mm*
Slot (s)	*6.5 mm*

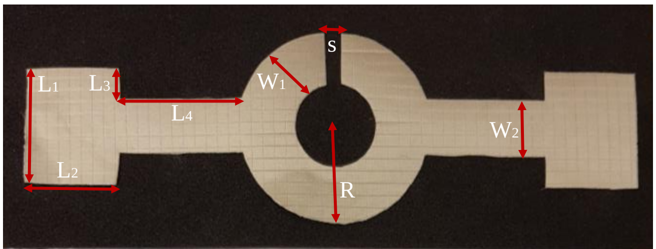
Fig. 1. Wrist antenna 1 with antenna dimensions. This antenna design has only a simple ring.

Next, we implemented two different wrist antennas that also had antenna bands going around the wrist, as presented in Fig 2 and Fig 3. The idea of these antenna band designs is that the human wrist will not fully cover the antenna. Similarly to the first wrist antenna design, the ring element will couple with the smaller ring and thus activate the IC when in close contact. The bands with radiating elements at the ends will go around the wrist and thus will be visible when the rings and the IC are close to each other under the wrist. Thus, we speculate to achieve a better wireless performance and a longer read range. The longer read range will allow us to build a larger user interface area around a single RFID reader, which means a more functional user interface, for example when used sitting by a table.



Length (L1)	*36 mm*
Length (L2)	*50 mm*
Length (L3)	*10 mm*
Length (L4)	*19 mm*
Radius (R)	*30 mm*
Width (W1)	*16 mm*
Width (W2)	*16 mm*
Slot (s)	*6.5 mm*

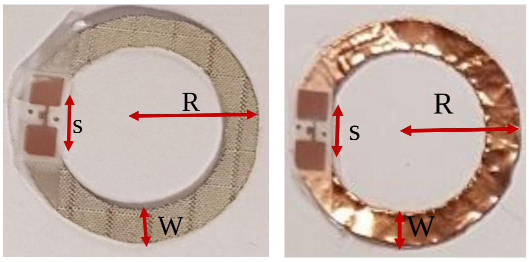
Fig. 2. Wrist antenna 2 with antenna dimensions. This antenna design has also an antenna band going around the wrist.



Length (L1)	*36 mm*
Length (L2)	*30 mm*
Length (L3)	*10 mm*
Length (L4)	*39 mm*
Radius (R)	*30 mm*
Width (W1)	*16 mm*
Width (W2)	*16 mm*
Slot (s)	*6.5 mm*

Fig. 3. Wrist antenna 3 with antenna dimensions. This antenna design has also an antenna band going around the wrist.

The design of the ID ring is presented in Fig. 4. These ID rings are small enough to be embedded into versatile structures. The ID rings presented in Fig. 4 are fabricated from electro-textile and from copper tape, in order to integrate them into clothing or into furniture and items. In the future, versatile manufacturing solutions can be used to integrate these ID rings into our surroundings, for example ID rings printed from conductive ink or paint, ID rings cut from copper tape, and ID rings embroidered with conductive thread directly into textiles.



Width (W)	*3 mm*
Radius (R)	*16 mm*
Slot (s)	*2 mm*

Fig. 4. ID ring with antenna dimensions fabricated from electro-textile (left) and copper tape (right).

B. *Tag Fabrication*

The electro-textile antennas were fabricated with nickel and copper plated Less EMF Shieldit Super Fabric (Cat. #A1220) as the conductor. For initial measurements, they were attached on a 2 mm thick EPDM (Ethylene-Propylene-Diene-Monomer) cell rubber foam. The electro-textile material has hot melt glue on the backside and can be easily ironed into textile substrates, such as clothing. The electro-textile material is light-weight and conformal with the touch and feel of regular clothing. The ID rings were cut from both the electro-textile material and from copper tape. The idea is that different materials can be embedded into different structures in different future use environments. In this study, the electro-textile antennas were integrated into clothing while the copper tape antennas were used on the table and items placed on the table.

The RFID IC used in this study was NXP UCODE G2iL RFID IC, provided in a fixture made of copper on a plastic film with $3 \times 3\ mm^2$ pads. We attached the pads to the electro-textile and copper tape ID rings using conductive epoxy (Circuit Works CW2400). This chip has a wake-up power of −18 dBm (15.8 µW). The IC component can be seen in Fig. 4, when attached to the ID ring antennas.

III. TESTING AND MEASUREMENTS

Firstly, we measured two samples of each wrist antenna type, with both an electro-textile ID ring and a copper tape ID ring. This initial evaluation was done in an anechoic chamber, in order to get an understanding of the wireless performance of these different types of antenna designs. Then, the actual evaluation measurements were started by first making a comparison of the wireless performance of the three different types of wrist antennas on-body. Next, the best one was selected for further testing, where the selected wrist antenna design was fabricated from the electro-textile material and ironed directly onto a shirtsleeve together with an electro-textile ID ring. This ready-made shirt was then used for practical evaluation of the developed system: A case study was conducted while sitting by a table where we had embedded copper tape-based ID rings.

A. *Initial Measurements*

The initial measurements were performed in an anechoic chamber (shown in Fig. 5) by using a Voyantic Tagformance RFID measurement system. The system is calibrated firstly by using a reference tag to characterize the properties of the wireless channel from the reader antenna to the tag. The theoretical read range between the tag and the reader antenna is then based on the measured path loss and threshold power, as given in (1),

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}\,L_{fwd}}} \quad (1)$$

where effective isotropic radiated power (EIRP) is the emission limit of an RFID reader, given as equivalent isotropic radiated power. In this study, EIRP = 3.28 W, which is the emission limit in European countries. λ is the wavelength transmitted from the reader antenna, P_{TS} and L_{fwd} are the measured threshold power and forward losses, correspondingly.

The results of the initial measurements between 800-1000 MHz are presented in Fig. 6. As can be seen, wrist antenna 1 shows similar read ranges of around 4-5 meters with both types of ID rings (fabricated from copper tape and from electro-textile). In case of wrist antennas 2 and 3, it can be seen that the read ranges are slightly longer when measured with the copper tape ID ring. This result is caused by the higher conductivity of the antenna material in the copper tape ID ring. Based on these initial measurements, the wireless performance of the fabricated wrist antennas is stable and the different wrist antenna types will be next compared on-body, in order to select the best one for practical testing.

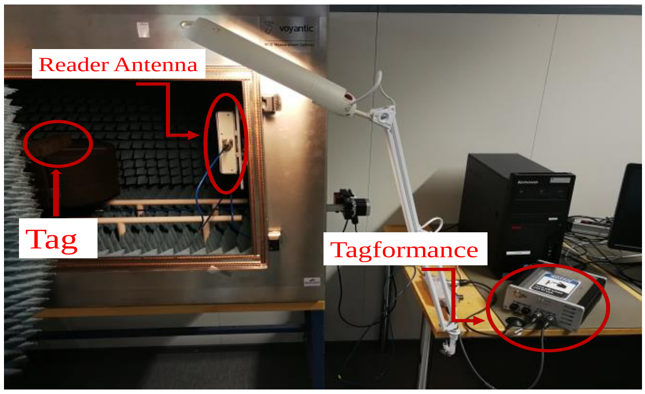


Fig. 5. Measurement set-up in an anechoich chamber.

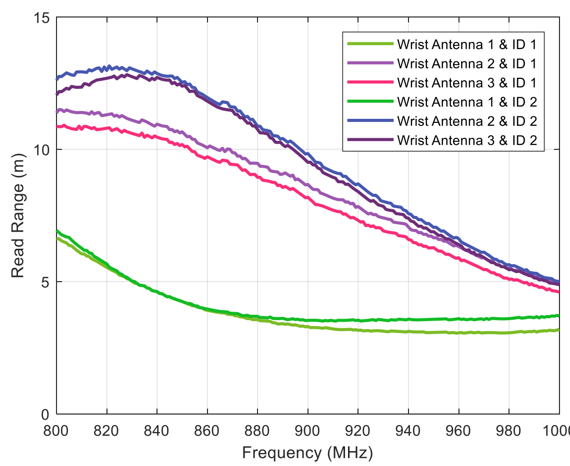


Fig. 6. Initial comparison of the three different wrist antennas and two types of ID rings (ID 1 = ID ring fabricated from electro-textile; ID 2 = ID ring fabricated from copper tape).

B. Tag Comparison

Firstly, the wrist antennas (attached on the black EPDM substrate) were simply taped into a shirt, as presented in Fig. 7. The copper ID rings were embedded into two different positions: on a table and on an item placed on the table. This used item was a piece of foam. Further, an electro-textile ID ring was attached into the other wrist of the shirt. This setup is presented in Fig. 8. We placed each of the three wrist antennas next to the three ID rings and manually (by using a measurement tape) measured the reading distance, i.e., the distance where the RFID reader was able to identify the specific ID of the ID ring.

The used mobile reader (Nordic ID Medea, which is designed for quick, accurate, and reliable data collection) measures the tags at 866 MHz, which is the European center frequency for UHF RFID systems, and then communicates with any background system though WIFI. As the reader is handheld and thus mobile, this user interface can be easily transferred together with the person using it.

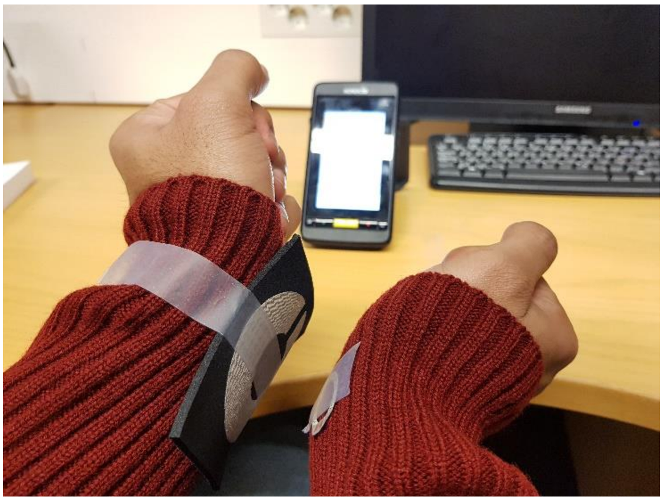


Fig. 7. Initial comparison of the three different wrist antennas: Antenna on a substrate is taped into a shirt wrist and an ID ring is taped into the other wrist of the shirt.

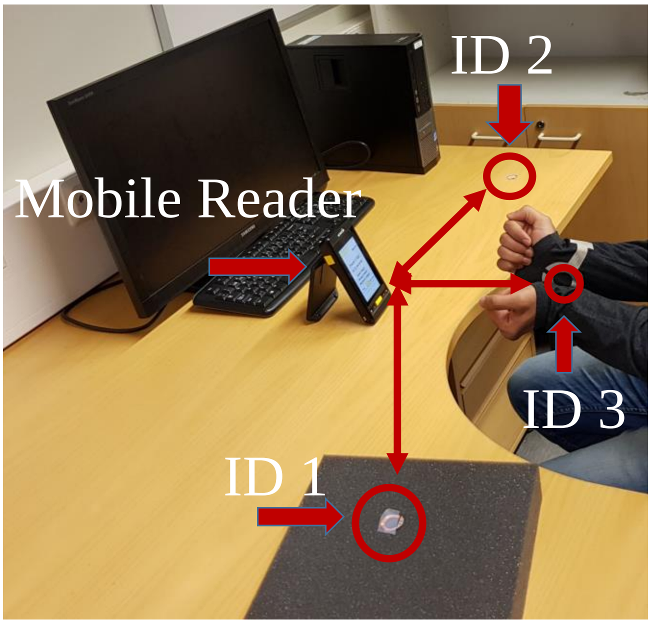


Fig. 8. Testing environment: Three ID rings are embedded into the environmnet (table, item, wrist), activated by the wrist antenna, and read by a mobile RFID reader on the table.

As can be seen from Table 1, while all the wrist antennas were able to activate the ID rings from distances of more than 30 cm, wrist antenna 3 showed significantly longer read ranges than the other two wrist antennas. This is due to the optimized wrist antenna design. We were able to detect the ID rings embedded into the table, item, and wrist from distances of 80 cm, 51 cm, and 56 cm, respectively. These results can be considered suitable for a user interface, which would be used when sitting by a table. Each ID ring can be used to activate a specific application or to give a specific input to an already activated application. As the read range from the ID ring on a table is 80 cm, these ID rings could be embedded all around a table. By moving the RFID reader, the user interface area can be modified easily.

TABLE I. WRIST ANTENNA COMPARISON: READING DISTANCES OF ID RINGS IN DIFFERENT POSITONS.

ID 1 (Item)	ID 2 (Table)	ID 3 (Wrist)
Wrist antenna 1 44 cm	Wrist antenna 1 36 cm	Wrist antenna 1 36 cm
Wrist antenna 2 45 cm	Wrist antenna 2 38 cm	Wrist antenna 2 40 cm
Wrist antenna 3 51 cm	Wrist antenna 3 80 cm	Wrist antenna 3 56 cm

C. Case Study

Next, wrist antenna 3 was selected to practical integration into clothing. The wrist antenna was ironed into a sleeve of a thin cotton-based shirt, while the ID ring was ironed into the other sleeve, as presented in Fig. 9. When wearing this shirt, the male test subject tested the ID rings on the table and on the item, as well as on the other sleeve, as presented in Fig. 8 and Fig. 10.

Fig. 9. Practical integration into clothing: Electro-textile wrist antenna and ID ring ironed directly into a shirt.

The clothing-integrated wrist antenna 3 showed excellent performance: We were able to use the setup presented in Fig. 8, while the mobile reader was at distances of 93 cm (ID ring on the table), 48 cm (ID ring on the item), and 58 cm (ID ring on the other shirt wrist). Thus, the performance of the clothing-integrated solution was similar or even better than the prototype solution taped onto the shirtsleeve. Each ID ring was read three times in a row, in order to confirm the wireless performance.

Fig. 10. Shirt-integrated wrist antenna is used to activate an ID ring on a table. This setup showed a read range of 93 cm.

IV. Discussion

These read range results are very promising, especially when considering the requirements of daily use of a clothing-integrated human-technology interface. The read ranges need to be long enough, in order to achieve large enough user interface area, which will enable convenient and seamless use of the solution. Since the mobile reader provides full mobility for the system, the practical applications are endless. As the system is cost-effective, passive, and maintenance-free, it can be seamlessly integrated into different type of clothing. Further, when coated with a protective coating, this user interface can also be washed with the garment.

The developed user interface has various application possibilities especially for special needs users. In addition to environmental controlling (opening doors, switching lights, using a music player), simple motivation and rehabilitation games could be developed. So we can use this interaction method of human-computer for any kind of output need on the computer's screen. In addition to this type of on/off controlling, more advanced controlling possibilities can be achieved by increasing the amount of ID rings, and then for example by using input patterns, such as swiping 2-3 ID rings in a row.

For patients with physical inabilities in hands, such as spasticity or muscle weakness, the solution enables game controlling without a need of holding a controller. It provides also alternative controlling method for patients with challenges in controlling precise movements (for example due tremor) or who has challenges in producing voice. Both of the before-mentioned symptoms occur for example in Parkinson's disease.

The mentioned on-body user interface controlled games could also be targeted for neurological patients for rehabilitation. To name an example, spatial neglect (a failure to report, respond, or orient to stimuli in contralesional space after brain injury that is not explained by primary sensory or motor deficits) rehabilitation could benefit from a game in which the player must become aware of the affected side by touching it with the healthy side [10]. The development of a game for rehabilitation purposes is part of our future work. Further, we envision that these ID rings and clothing-integrated wrist antennas could be used to transform our daily environments into intelligent user interfaces for human-technology interaction.

V. Conclusions

There is an urgent need for a human-technology user interface that allows touchless, simple and instinctive input actions into different applications. We presented a cost-effective and maintenance-free passive UHF RFID-based solution, which can be seamlessly integrated into our clothing and into our living environment. Our solution had two novel features: hand movement-based activation and around hand antennas. These features allowed reliable and natural hand movement-based interaction and increased read ranges. Based on this first setup, which was built around a person sitting by a table, the read ranges of our solution are suitable for practical use. It was shown that the system can be integrated into clothing as well as into the table surface and into items on the table. Thus, based on these preliminary results, this system can be considered a promising solution for future human-technology interaction. The next step is practical testing of our solution with home environment applications, such as controlling of music and lights, as well as development of a serious game for rehabilitation purposes.

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PUBLICATION II

Body Movement-Based Controlling Through Passive RFID Integrated into Clothing

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Body Movement-Based Controlling Through Passive RFID Integrated into Clothing

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***Abstract*—We present a passive ultra-high frequency (UHF) radiofrequency identification (RFID)-based strain sensor, which is designed for simple and efficient body movement monitoring. This RFID platform is fabricated from electro-textile materials and can thus be seamlessly integrated into our everyday clothing. The sensor platform has an integrated reference tag, in order to avoid the effects of reflections or external disturbances on the sensor tag performance. This sensor platform prototype has an on-body read range of 1 meter in a normal office environment with an off-the-shelf RFID reader. The wireless performance of the sensor tag has a significant change caused by arm elongation. Thus, the sensor functionality can be based on variation of the sensor tag's backscattered power percentage (Δ*P* %). Based on the preliminary results achieved in this study, this passive and cost-effective sensor platform could be an efficient future way to turn human gestures into inputs for digital devices.**

***Index Terms*—Human-technology interface, passive UHF RFID, strain sensor, clothing-integrated electronics, backscattered power.**

I. Introduction

PASSIVE RFID (radio frequency identification)–tags, especially in the UHF (ultra-high frequency) range, have already showed promising preliminary results when applied for body movement monitoring. When fully functional, such monitoring would allow us to use human gestures as direct human-technology interaction inputs, which would make use of technology simple and natural. As the passive RFID technology is maintenance-free as well as extremely cost-effective, it has significant advantages over traditional on-body interface solutions, which either require the person to be directly seen or need to be equipped with an on-board energy source [1]-[11]. These requirements for example increase the price of such solutions, cause them to require maintenance, or limit their use environments.

As mentioned, variations of backscattered signals from wearable passive RFID tags have been shown to provide information about human body positions and movements [12]-[17]. Touching an RFID tag with finger has also been shown to cause a change in the tag's backscattered signal [18][19], which can then be measured and turned into a wireless input. Integrating sensing capabilities into passive RFID tags has been studied for years, and by tracking changes in their backscattered signals, these tags have been used for sensing without external sensors. Due to the significant effects of mechanical stresses and water on passive RFID tag performance, these tags have especially been tested as strain [20]-[23] and moisture [24]-[26] sensors.

In this article, we present an extended study of our previous work related to clothing-integrated passive UHF RFID-based strain sensor platform [27]. Now, we integrate a reference tag to the sensor platform, which holds a stable wireless performance during the elongation of the strain sensor tag. Thus, we can avoid the effects of reflections or external disturbances on the sensor performance. This will make our sensor tag functional from different distances and in different use environments. Further, instead of working in an anechoic environment, we test the platform in normal office conditions with an off-the-shelf RFID reader. Moreover, the sensor platform is tested on both arms of a male subject, which is important, as the human body is asymmetric. RFID-based and clothing-integrated wireless control of technology has also been studied in our two previous papers [28][29].

The used textile antenna materials are commercial electro-textiles, which have a feel and look of traditional fabrics. Thus, our sensor tag and reference tag can be seamlessly integrated into clothing. As clothing is stretching and bending along the human body movement, in any clothing-integrated solutions, antennas, electronics, and especially interconnections are under a strong stress, which results as electrical and mechanical reliability challenges. Furthermore, as the wearable RFID antenna dimensions change along body movement, this movement may cause the antenna-IC (integrated circuit) matching to change [30]-[32]. Thus, as presented in [27], we are using a two-part sensor tag antenna design, where the small feeding loop part of the antenna, including the antenna-IC interconnection, can be protected from mechanical stresses during elongation of the radiating antenna. This type of RFID antenna design protects the interconnections between the clothing-integrated antennas and IC components.

II. Platform Manufacturing

The structure and dimensions of the sensor tag antenna and the reference tag antenna are shown in Fig. 1. As explained with more details in [33], the sensor tag antenna design has two

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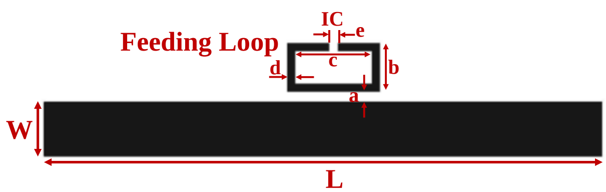
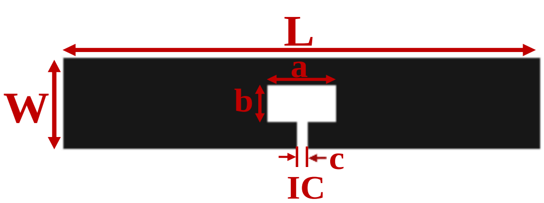
separate parts, the feeding loop and the radiating antenna, with a 2.5 mm gap between them.

The radiating antenna of the sensor tag was fabricated from stretchable commercial conductive textile, Less EMF Stretch Conductive Fabric [34]. The feeding loop and the reference tag were both cut from non-stretchable nickel plated Less EMF Shieldit Super Fabric [35]. The used microchip component is NXP UCODE G2iL series RFID IC, which was attached to the feeding loop with conductive silver epoxy. The details of the reference tag fabrication are explained in [27]. As shown in Fig. 2, the fabricated sensor platform and the reference tag were finally attached on a cotton-based shirt using normal textile glue. The reference tag is placed on a part of the arm that remains at the same position when facing the reader antenna.



a	b	c	d	e	L	W
2.5	11.3	21.6	1.9	2	135	12.6



a	b	c	L	W
14.3	8.125	2	100	20

Fig. 1. The designs and dimensions in (mm) of the sensor tag antenna (top) and reference tag antenna (bottom).

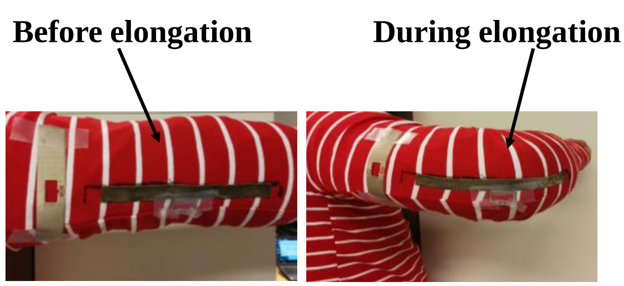


Fig. 2. A ready strain sensor platform (including the sensor tag and the reference tag), integrated into a cotton-based shirt.

III. Measurements and Results

In this study, the strain sensor platform is attached to the arm of a slightly stretchable cotton-based shirt, and tested in an office environment. Normal office environment with wooden and metallic furniture, as well as continuous use of wifi and mobile phones, is a challenging environmnet for these passive RFID-based sensors. The backscattered signals of the sensors are noisy and unstable, as they are affected by the environment. In our previous study [27], the first version of this strain sensor was measured in an anechoic environment. The achieved read ranges when the arm was straight/bended were around 5 and 2.5 meters, respectively. In this study, we want to evaluate the performance in a more realistic environment.

The measurement setup includes a Thingmagic M6 RFID reader, which is connected to a circularly polarized reader antenna through a connecting cable and wirelessly to a laptop with wifi. In this study, we are following the European RFID requirements and working at the standard frequency (865.6-867.6 MHz). The transmitted power is 28 dBm.

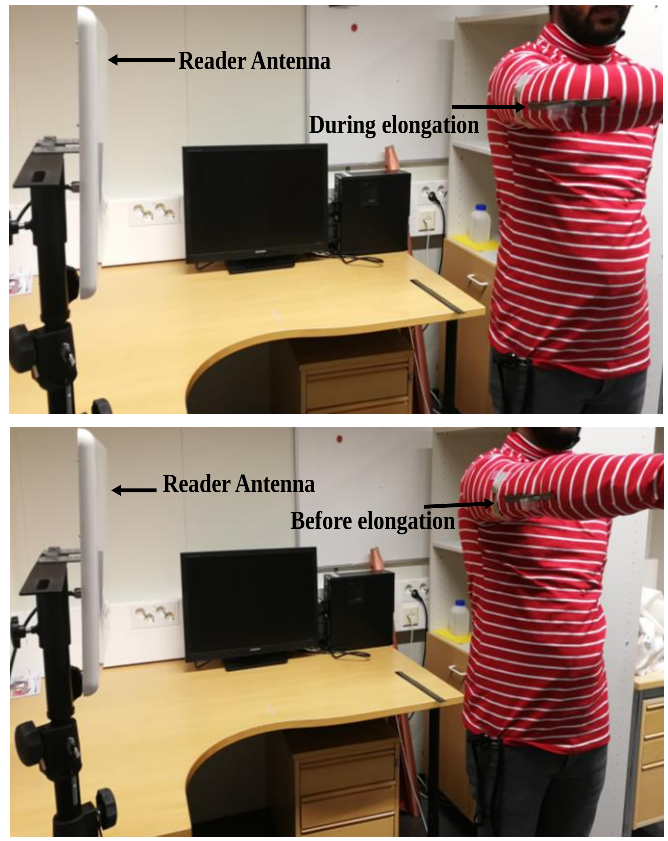


Fig. 3. The measurement setup of on-body measuremnts in an office environment: during elongation (top) and before elongation (bottom).

We firstly measured the backscattered signal power of the sensor tag (in the presence of the reference tag) at different distances from the reader antenna. The measurements were done when the arm was held straight and when it was slightly bent (to at least around 30°). All the measurements were done in an office environment.

TABLE I
THE BACKSCATTERED SIGNAL POWER OF THE SENSOR TAG (DBM) IN AN OFFICE ENVIRONMENT (LEFT ARM).

Read range	70 cm	80 cm	90 cm	100 cm
Straight	-66	-68	-70	-71
Bent ≥30°	-70	-70	-71	-71

TABLE II

THE BACKSCATTERED SIGNAL POWER OF THE SENSOR TAG (DBM) IN AN OFFICE ENVIRONMENT (RIGHT ARM).

Read range	70 cm	80 cm	90 cm	100 cm
Straight	-67	-69	-70	-71
Bent ≥30°	-68	-70	-71	-71

Table I shows these results on the male test subject's left arm and Table II on the right arm. As shown, the sensor platform prototype currently works at a distance of 1 meter. This read range is already suitable for some practical applications, for example when considering a home environment. However, the on-body antenna design needs to be optimized for the next sensor platform version. The goal is to achieve a read range of around 2.5 meters, which would be suitable for many application environments.

Fig. 4 shows the change in the backscattered power of the strain sensor tag before elongation and during elongation on (left/right) arm for 100 read counts. This test was done by a male test subject in an office environment. The results were confirmed by performing multiple cycles. The number of times a tag has been read by the reader is called a read count. In this measurement setup the reader reads each tag 10 times in 1 second. The sensor tag is in normal state when the arm is held straight and it is elongated when the arm is bent to 90°, as presented in Fig 3. The reference tag has a stable behavior in all situations, while in an arm bending angle of more than 50° can be read from the backscattered power of the sensor tag. As presented in [36], the change in the performance of a dipole antenna is not significant when curving is below 180 degrees. This implies that the change is mainly due to the stretching of the strain sensor. The strain sensor shows a slightly different performance in the left and right arm. It is due to the asymmetric human body and a slight difference in the placement of the sensor tag in the shirt.

We are calculating the variation of the backscattered power as $\Delta P\ \% = \left|\frac{P_{sns}-P_{ref}}{P_{ref}}\right|$, where P_{ref} and P_{sns} represent the backscattered power from the reference tag and the sensor tag, respectively. As Fig. 5 shows, ΔP % and the difference between its final (during elongation) and initial value (before elongation) is more than 0.10 for both arms. This 0.1 value of ΔP % for each division on y-axis corresponds to 10 % change.

The sensor tag behaves normally during the arm (left/right) bending between around 0-45° and 0-50°, respectively, and ΔP % value remains constant. At 90°, the arm bending caused the maximum elongation and a significant change in ΔP % value. The difference of ΔP % is quite significant before and during elongation, i.e. 0° and 90°, which enables us to decide about the state of the arm, i.e. either it is straight or bent.

Fig. 6 shows the change in the backscattered power of the strain sensor tag before elongation and during elongation on (left/right) arm for 100 read counts. This test was done by a male test subject in a home environment. Fig. 7 shows the difference in ΔP % value for final and initial value, which is more than 0.20. The difference is quite visible in terms of percentage, as it counts for more than 20 % change in the value. Finally, the results for a female test subject in a home environment are shown in Fig. 8 and Fig. 9. The difference in ΔP % has a value more than 20 % as well.

Thus, the first version of this strain sensor can already work as an on/off type of sensor. However, our goal is to achieve a more accurate output in the future. The plan is also to make the sensor platform washable, reliable when facing mechanical stresses, as well as smaller in size, in order to be integrated into smaller joints of body.

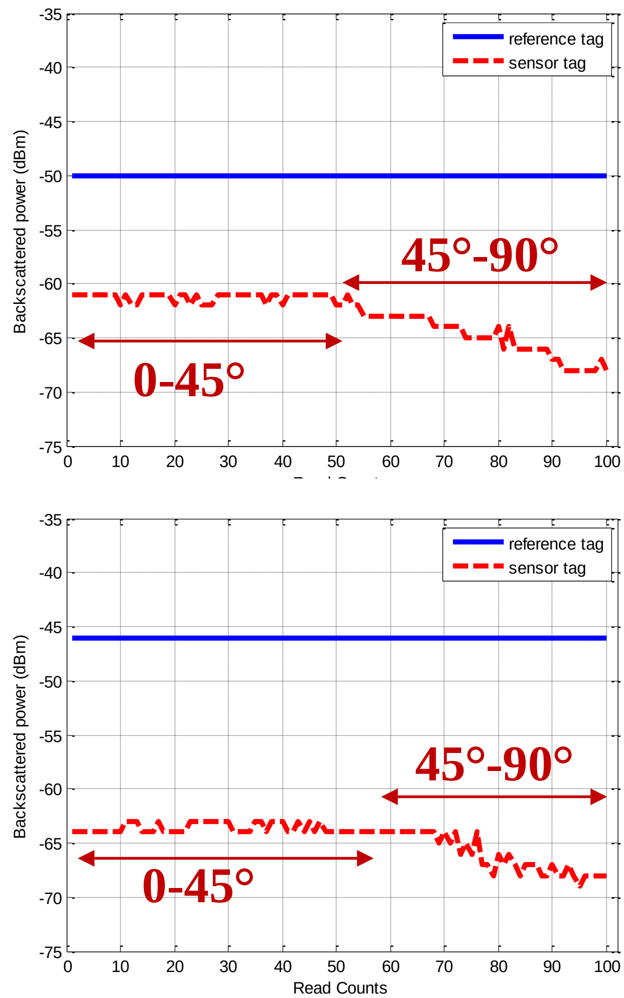


Fig. 4. The backscattered power of the strain sensor tag and the reference tag before and during elongation for left arm (top) and right arm (bottom) in an office environment by a male test subject.

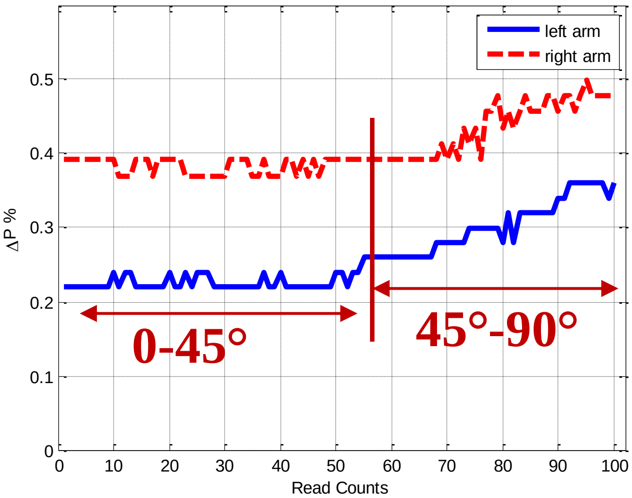


Fig. 5. The calculated ΔP % of the sensor tag for left/right arm in an office environment by a male test subject.

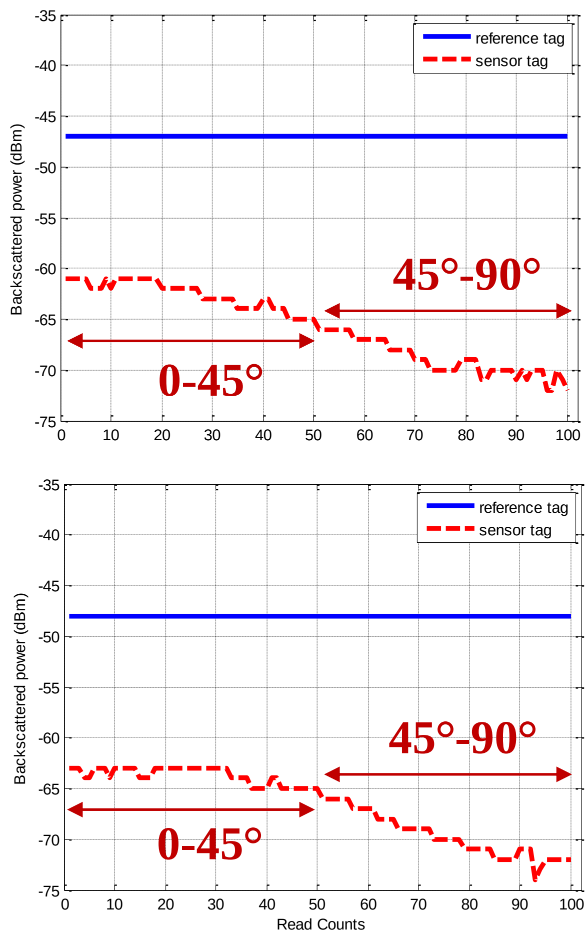


Fig. 6. The backscattered power of the strain sensor tag and the reference tag before and during elongation for left arm (top) and right arm (bottom) in a home environment by a male test subject.

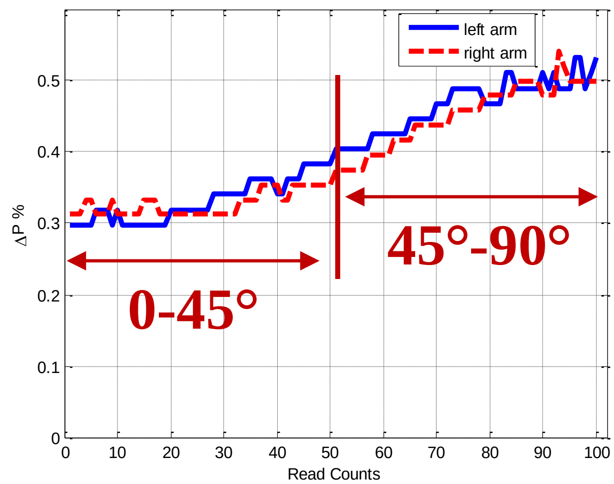


Fig. 7. The calculated ΔP % of the sensor tag for left/right arm in a home environment by a male test subject.

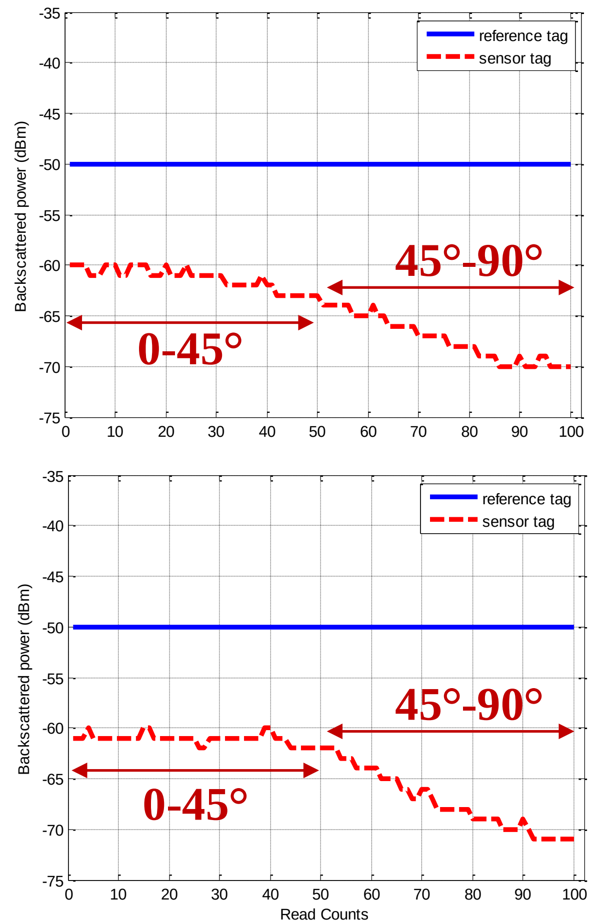


Fig. 8. The backscattered power of the strain sensor tag and the reference tag before and during elongation for left arm (top) and right arm (bottom) in a home environment by a female test subject.

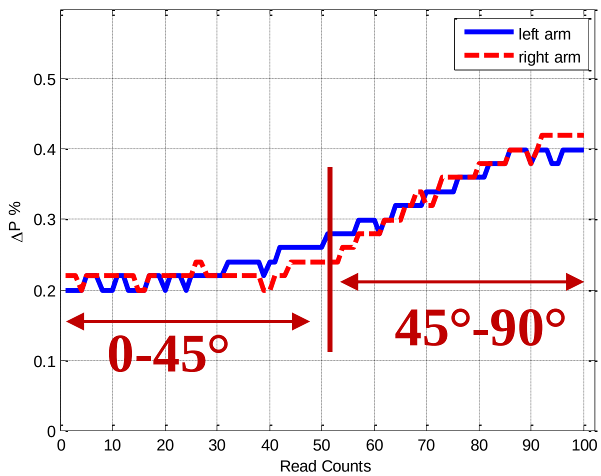


Fig. 9. The calculated ΔP % of the sensor tag for left/right arm in a home environment by a female test subject.

IV. Discussion

Although these preliminary results are promising, a larger amount of measurement data from different people is needed to truly evaluate the possibilities of this strain sensor platform. Our plan is also to test these sensors on other parts of the body, such as in legs and back. As each sensor tag has a unique ID, they can be combined into RFID sensor tag network, where the IDs and backscattered signals of several tags can be monitored and recorded. Such a sensor tag network would allow accurate monitoring of the movement of the whole body.

There are a lot of touch-based and voice-operated devices available, which are not ideal for all the users because of different disabilities. Another approach is to use artificial intelligence and cameras to track body movements for controls. However, the use of cameras might cause ethical issues, if the video data is sent for analysis to cloud, for example. Our developed sensor user interface provides another option for human-computer interaction. It has a wide range of applications from smart housing to special need users, environmental controlling, and communication. Currently available mobile devices are already taking a larger role in health monitoring and rehabilitation. In the future, this type of sensor platform may enable interactions through joint movement and thus could be used for supporting exercising and rehabilitation as well. The controlling method can be tailored according to disabilities (which joint can be moved) or rehabilitation needs (which limbs needs exercise). Further development for sensor platform might also create opportunities to track vital signs, such as breathing, which also creates a small strain on chest.

V. Conclusion

Our paper introduced a new type of clothing-integrated human-technology interface, based on the wireless behavior of a strain-sensitive passive UHF RFID tag antenna. The performance of this cotton shirt-integrated sensor platform was examined on-body by backscattered signal power measurements. The strain sensor tag and the reference tag integrated together were tested on the left and right arms of a male test subject. The bending of the arms between 0-90° can be observed from the variation of the backscattered power (ΔP %). The difference between the platform's final (during elongation) and initial value (before elongation) is more than 0.10 for both arms. This 0.1 corresponds to a variation of 10 %, which corresponds to 17-20 dB change in the backscattered power in an office environment, while in a home environment it corresponds to around 10-12 dB change in the backscattered power. Both are significant enough changes to work in versatile real-life applications. Thus, it is possible to record human arm movement with these shirt-integrated simple and passive RFID components.

Although these results are still preliminary, they are encouraging. When human-technology interfaces are integrated into our clothing, they will turn into a seamless part of our everyday life. A clothing-integrated interface is extremely interesting, for example when considering smart home applications, rehabilitation and exercise monitoring, virtual reality, as well as gaming. For example, the sensor could be used for counting the movements of elbow, knee, and chest in exercise monitoring or it could be utilized as a controller in an embodied game. The next steps of our work are to optimize the sensor antenna design, in order to achieve a longer read range and more accurate monitoring of arm movement. We will also test the system in an environment with more disturbance, for example several moving people, in order to ensure the stable performance. Further, we will be testing such sensor platforms on other parts of the human body as well, for example in legs and back. The future work will also include development of practical applications, such as games for rehabilitation and activation.

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PUBLICATION III

ClothFace: Battery-Free User Interface Solution Embedded into Clothing and Everyday Surroundings

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ClothFace: Battery-Free User Interface Solution Embedded into Clothing and Everyday Surroundings

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***Abstract*— This paper introduces ClothFace, a passive ultrahigh frequency (UHF) radio frequency identification (RFID) -based user interface solution, which can be embedded into clothing and into our everyday surroundings. The user interface platform consists of RFID tags, each of which has a unique ID. All the tags are initially readable to an external RFID reader. A specific tag can be switched off by covering it with a hand, which change can then be used as a digital input to any connected device. Because of the used passive UHF RFID technology, there is no need for embedded energy sources, but the interface platform gets all the needed energy from the external RFID reader. In this study, two test setups were created to an office environment: For the Body Test, the interface was integrated into a cotton shirt and into an item. For the Table Test, the interface was integrated into a wooden table. A gamelike testing software was created for both setups and two male test subjects tested the platform. The achieved results were very promising: success rates of 99-100 % and 94-98 % were reached in the Body Test and in the Table Test, respectively. Based on these promising preliminary results, we can envision the employment of ClothFace for developing multi-modal interfaces that can provide on-body gestural controls in body-based serious game applications.**

Keywords—gestural control, passive UHF RFID, textile electronics, user interface, wearables.

I. Introduction

Although interaction with technology is an essential part of our everyday life, for many people, different limitations and disabilities are preventing the benefits that versatile digital devices could offer [1]-[3]. For many people, the use of screen-based functionalities is not possible. The available alternatives for screen-based functionalities are usually voice- or body movement-based [4]-[8]. Voice-controlled interfaces have their own challenges, such as linguistic coverage and privacy issues. As an alternative, gesture-based solutions have been suggested [9]-[12]. The current body-movement based solutions have certain limitations, as they either require a line-of-sight to work, an on-board energy source, or they are only useful in a specific configuration.

Passive ultra-high frequency (UHF) radio frequency identification (RFID) is a technology traditionally used for wireless identification and item tracking. This technology consists of battery-free and wirelessly operated tags. The tags draw energy wirelessly from an external RFID reader antenna and respond by sending their unique ID by backscattering. These tags are functional from distances of several meters.

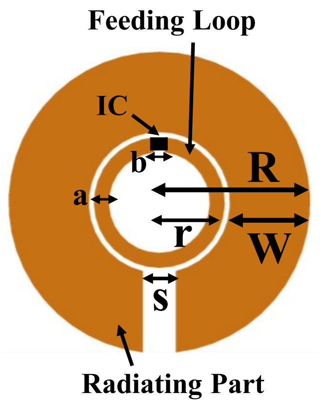
Passive UHF RFID tags can be attached to human body or embedded to the surrounding environment. The backscattered power of an RFID tag changes when a person interacts with the tag, either by touching the tag with finger or by stretching or relocating the tag by body movement [13]-[17]. The change in each RFID tag's backscattered signal power can be monitored. Thus, the changes caused by body movements could then be used for controlling technology [18]-[20]. For the reasons above, the technology has emerged as a cost-effective, battery-free, and multidimensional technology for body movement monitoring and human-technology interaction. The main challenges in these solutions are the noisy and unstable backscattered signals of RFID tags.

In this paper, we present ClothFace, a passive UHF RFID-based user interface solution, which can be integrated into clothing and into our everyday surroundings. The user interface platform consists of RFID tags, each of which has a unique ID. All the tags are initially readable to an external RFID reader. A specific tag can be switched off by covering it with a hand, which change can then be used as a digital input to any connected device. Two different test setups are created to an office environment: For the Body Test, the interface is integrated into a cotton shirt and into an item. For the Table Test, the interface is integrated into a wooden table. Further, a gamelike testing software is created for both test setups.

II. Design and Manufacturing of Tags

A. Designs of Body and Item Tags

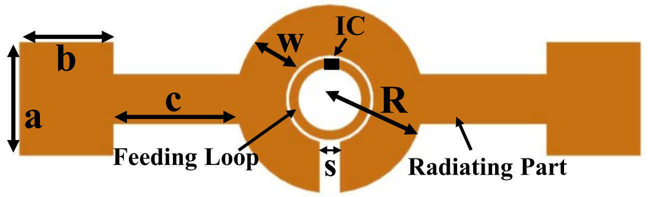
Firstly, we present the Item Tag, which has a two-part antenna. The antenna design and its dimensions can be seen in Fig. 1. This type of antenna has been previously presented e.g. in [21]. The first part of the tag antenna is the bigger radiating antenna. The second part is the smaller feeding loop with the RFID IC (integrated circuit) component, holding the unique ID of the tag.



W	R	s	a	b	r
18	30	6.5	3	2	16

Fig. 1. Item Tag antenna design (radiating antenna) with dimensions [mm]. Feeding loop with dimensions [mm] is inside the radiating antenna.

Secondly, we present the Body Tag, which also has a two-part antenna, including the radiating part and the feeding loop part shown in Fig. 2. This antenna has already been successfully tested near the human body in [21]. As this tag antenna has been designed for on-body solutions, it can be used on different body parts.



a	b	c	s	w	R
36	30	39	6.5	16	30

Fig. 2. Body Tag antenna design (radiating antenna) with dimensions [mm]. Feeding loop inside the radiating antenna is like the one in Fig. 1.

B. *Fabrication of Tags*

The Body Tags (radiating antenna and feeding loop) are fabricated from an electro-textile material, which is nickel and copper plated Less EMF Shieldit Super Fabric (Cat. #A1220). Both parts of the antenna are cut from the electro-textile material and then attached to a cotton shirt by ironing over them, as the backside of this material contains hot-melt glue. Both parts of the Item Tag are fabricated from copper tape and fixed on the surface of a wooden table surface and an item (which is a piece of styrofoam). This copper tape has glue on the backside, so the antennas are simply positioned to their places.

The RFID ICs are attached to the feeding loops of both type of tags. This IC belongs to NXP UCODE G2iL RFID microchips (a wake-up power of −18 dBm, 15.8 μW) and it comes with two copper pads (each 3×3 mm^2) fixed on a plastic strap. These copper pads are attached to the copper and electro-textile feeding loop rings with conductive epoxy glue (Circuit Works CW2400). All the ready-made tags can be seen in Figs. 3-5.

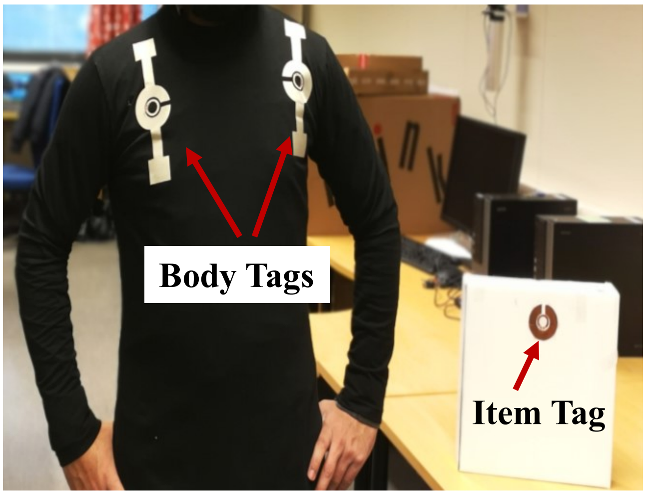


Fig. 3. Ready-made Body Tags (from electro-textile) and Item Tag (from copper tape) integrated into the cotton shirt and into the item on a table.

III. Practical Testing of ClothFace

A. *User Interface Platforms and Testing Setups*

The measurement setup includes Thingmagic Mercury M6 RFID reader, which operates at the European standard frequency range (865.6-867.6) MHz and a circularly polarized RFID reader antenna connected to the M6 reader through a connecting cable. The reader system is connected to a computer through WIFI. The used operating power for the M6 reader in this study is 28 dBm.

The measurement environment, which is a normal office, is challenging for passive UHF RFID tags, due to the many other electrical devices, wireless signals, and human movement inside the office. This testing environment is thus perfect for evaluating the practical usability of the ClothFace user interface platforms.

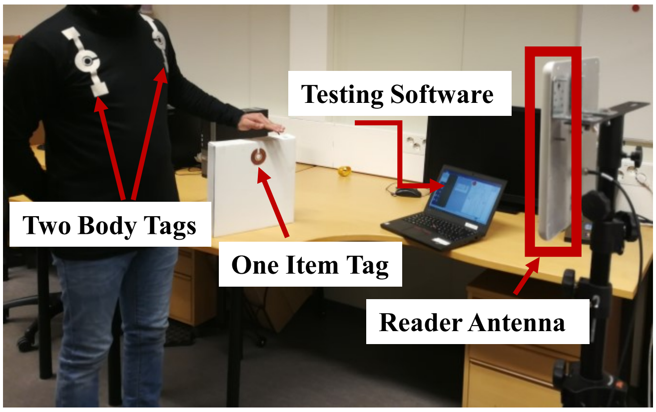


Fig. 4. Test setup for the Body Test: Two Bogy Tags are integrated into the cotton shirt and one Item Tag is attached to the item on a table. Each tag is "selected" by covering it with a hand.

For the Body Test, the interface is integrated into the cotton shirt and into the item on the table. This setup can be seen in Fig. 4 and it includes two Body Tags and one Item Tag. The distance between the interface and the reader antenna is 100 cm. For the Table Test, the interface is integrated into a wooden table. This setup can be seen in Fig. 5 and it includes three Item Tags. The distance between the interface and the reader antenna is 70 cm.

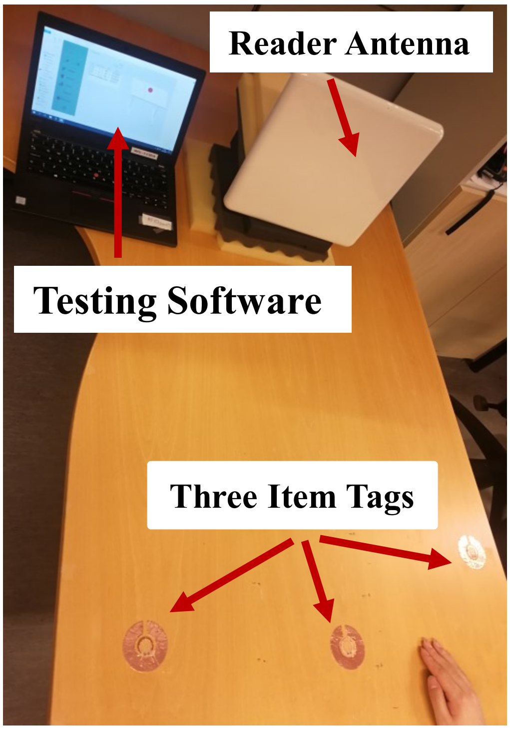


Fig. 5. Test setup for the Table Test: Item Tags 1-3 are integrated into the wooden table. Each tag is "selected" by covering it with a hand.

The used RFID tags are initially readable for the M6 reader. A specific tag can be "switched off" by covering it with a hand, which will then be used as an input to a testing software. A gamelike testing software is developed for both test setups. The testing software is developed on .Net framework with C# as windows forms application. It uses ThingMagic Mercury API tools to control the M6 reader and filter received RFID tag IDs to focus only on the ICs on test (and not to be disturbed by any surrounding RFID tags). The ThingMagic Mercury API supports continuous reading, so it is chosen to retrieve RFID tags from the M6 reader.

The developed testing software screens for the Body Test and for the Table Test are shown in Figs. 6 and 7, respectively. Initially, the software shows a random red point on the screen, to which the user must act accordingly, and switch off that specific tag, by covering it with his/her hand. If a correct input is given by the user, a green point appears on the screen, while the software stores the input as "1" in an excel sheet. If a wrong input is given, or there is no input in 5 seconds, the software stores it as "0". The excel sheet contains the information about asked input, given input, and if the given input was correct or incorrect. The gamelike testing software is designed for initial testing of the interface. It will thus be further developed and tested by more users in the future.

ClothFace user interfaces in the Body Test setup and in the Table Test setup are tried by two male subjects. In both test setups, both subjects are given 100 random inputs by the testing software. The test subjects are facing the reader antenna directly.

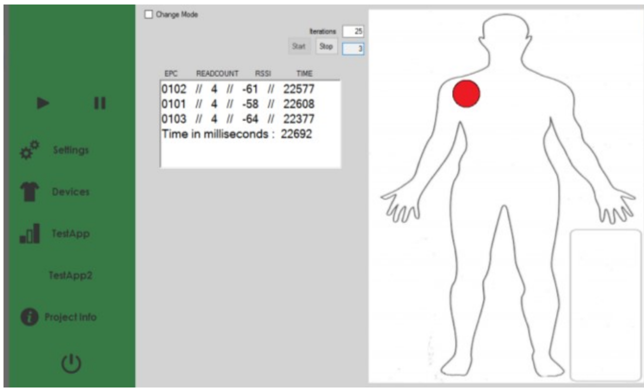


Fig. 6. Testing software screen for the Body Test: The red circle is asking for the Body Tag on the right side to be selected.

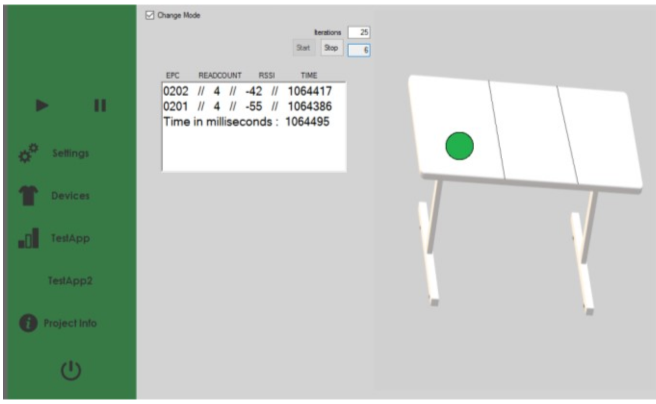


Fig. 7. Testing software screen for the Table Test: The green circle is showing that the Item Tag on the left has been correctly selected.

B. Measurement and Testing Results

The backscattered power of a specific tag with a distance "d" between the tag and the reader antenna is given in (1).

$$P_{rx} = P_{tx} G_{tag}{}^{2} G_{reader}{}^{2} \left(\frac{\lambda}{4\pi d}\right)^{4} \alpha |\rho_1 - \rho_2|^2 \quad (1)$$

where P_{tx} is the transmitting power, G_{tag} is the gain of the tag antenna, G_{reader} is the gain of the reader antenna, λ is the wavelength, d is the distance between the reader and the tag antennas, α is the modulation coefficient, ρ_1, ρ_2 are the power wave reflection coefficients of the tag in two different impedance states of the IC.

As indicated in Table I, the backscattered powers of the tags in the Body Test and in the Table Test are similar for both testers, -53 to -56 dBm for the Body Test and -42 to -49 dBm for the Table Test. The distance between the user interface platform and the reader antenna naturally has a significant impact on the backscattered power.

TABLE I. INITIAL BACKSCATTERED POWERS OF THE TAGS IN THE BODY TEST AND IN THE TABLE TEST SETUPS.

Tester	Body Test			Table Test		
	Body (left)	Body (right)	Item	Left	Middle	Right
U1	-55	-56	-54	-46	-42	-49
U2	-54	-53	-56	-47	-42	-49

TABLE II. SUCCESS RATES OF THE TWO TESTERS IN THE BODY TEST AND IN THE TABLE TEST.

Tester	Body Test	Table Test
U1	99 %	98 %
U2	100 %	94 %

The achieved testing results of the both test subjects from the Body Test setup and the Table Test setup are shown in Table II. The success rates for the Body Test are very high (99-100 %), but the results from the Table Test are very promising too (94-98 %).

IV. Discussion and Further Applications

As a result of this preliminary study, we have successfully integrated ClothFace technology into a wooden table, into a cotton shirt, and into an item on a table. The achieved first testing results are promising and support further development of the solution.

The ClothFace tags can provide various opportunities for contributing to on-body gestural interaction. One of the most important features of ClothFace is that it does not need any on-body energy source, so that users can interact with their clothes in areas where RFID receiver coverage is available. Embedding of those antennas to cloths is relatively easy and low-cost compared to solutions that requires more electronic components to be embedded on the body, such as Jacquard, which uses conductive threads and a Bluetooth transmitter [22] or Botenial, which relies on EMG and capacitive sensing [23]. By combining this technology with previous applications on UHF RFID [17][21], it would be possible to create on-body location sensitive gestural systems capable of distinguishing input methods, such as hovering and touching, which are challenging as reported by previous work [23]. Moreover, it is also possible to detect sequential readings of hidden tags on the body for programming different body-based mid-air gestures (i.e. hovering on three tags from chest to waist can be programmed to decrease the volume of a sound system).

In this direction, we see many potentials in ClothFace for employing it to many different applications regarding Serious Games and Medical Applications. The versatility of systems that can be developed with the combination of previous [17][21] and the current UHF RFID-based solutions promise the integration of wide array of on-body commands. For example, while most of the systems only can use the body-surface as a touch surface, combination of those systems can provide applications, where hover (mid-air) and touch gestures can be used together. These can provide great opportunities for body-based exergames. As put by game design literature, primary aim of the games is providing fun and pleasurable time [24]. Those qualities are critical for a game to be engaging and immersive. Previous studies on body-based games put forth many guidelines about how to utilize the body for revealing those fun activities. One of the recent works on body-based games indicated that the relationship between körper (the material body) and leib (the experiencing body) should be comprehended thoroughly for the employment of compelling bodily playful experiences [25]. In that sense, ClothFace, even as a novel game control modality, has the potential to uncover playful interactions around the body. Previous work also put forth that the novel utilization of the bodies as game controllers can turn the controlling activity itself into a game [26]. For example, in a game setting, while a hover gesture could activate a specific skill that is effective for a certain type of situation, a touch version of the same gesture that can be employed to the same part of the body can activate another skill. The challenge provided by changing between those different kinds of modalities can provide a simple engagement, make users perform required bodily activity, and can also reveal somesthetic interaction qualities [27] by overcoming the interference caused by the problems of tracking technologies.

Other than these, with the introduction of hands-free systems in virtual reality systems, the need for additional controllers can be satisfied by wearables that would incorporate ClothFace system. Employment of such wearables would allow more diversity in terms of body interaction and control modalities in virtual reality systems, which have started to be important platforms for serious games [28][29]. The hovering method of ClothFace can also provide advantages in environments, where touching to surfaces or cloths are risky such as intensive care units in hospitals. Our plan is, that the prototype will be further upgraded in design, as well as tested in different environments by more people.

V. Conclusions

In this paper, we tested ClothFace, a passive UHF RFID-based user interface platform, which was integrated into a wooden table, into an item on a table, and into a cotton shirt. This technology is battery-free and extremely cost-effective, which makes it appealing for daily use. These first prototypes were fabricated from copper tape and electro-textile materials and both materials proved out to be suitable for this type of use. For the Body Test, the interface was integrated into a cotton shirt and into an item. For the Table Test, the interface was integrated into a wooden table. A gamelike testing software was created for both setups and two male test subjects tested the platform. The achieved results were very promising: success rates of 99-100 % and 94-98 % were reached for the Body Test and for the Table Test, respectively. Although these results are preliminary, they provide promising evidence of employing multimodal gestural control, including on-body touch and hover methods that can be advantageous in developing body-based serious game applications in different kinds of media.

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PUBLICATION IV

Passive UHF RFID-based User Interface on a Wooden Surface

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Passive UHF RFID-based User Interface on a Wooden Surface

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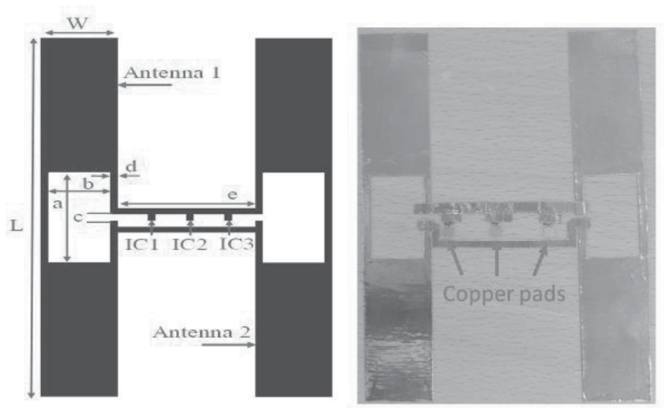
Abstract— We present a passive ultra-high frequency (UHF) radio frequency identification (RFID)-based human-technology interface platform. The platform comprises of two dipole antennas and three integrated circuits (IC), each with a unique ID. The platform, which is fixed on a wooden table by cutting the antennas and antenna-IC interconnections from copper tape, can be used for push button and swipe controlling. Each IC can be activated, i.e., connected to the antennas, by touching with finger. As the RFID reader can be connected to any application through WIFI, these ICs can act as wireless input points integrated into furniture, items, and textiles, where they can be used as inputs to desired digital actions. The platform allows all connected devices to be controlled accurately and effortlessly, which will take the convenience of implementation and utilization of these systems to a new level. As a preliminary trial, the platform was tested by two people giving 200 random inputs and 98% and 99% success rates were achieved. Based on these results, this type of passive RFID-based solutions could be used for administrating interfaces that would administer wide variety of interaction modalities, such as touch or tangible interaction on flat surfaces (e.g., tabletop surfaces, walls, doors).

1. INTRODUCTION

Passive UHF (ultra-high frequency) RFID (radio frequency identification)-technology has revolutionized logistics and supply chain management by offering wirelessly addressable cost-effective and maintenance-free identification and tracking solutions. However, this versatile technology also has several other application possibilities, such as establishment of energy-autonomous wireless sensors [1–7]. Interaction with technology has become extremely important in our everyday lives. Due to people's versatile disabilities and limitations, current handheld, screen-based and touch- or voice-operated devices are not ideal for all consumers and all situations [8–10]. Thanks to the passive nature and cost-effectiveness of passive RFID technology, its potential for human-technology interfaces has been noticed. For example, it has been shown that when a user actually touches an RFID tag with finger, it manifests as a change in the phase of the tag's backscattered signal [11, 12]. Thus, simple RFID tags could offer touch-based solutions for human-technology interaction. However, the noisy and unstable backscattered signal is not a very convenient solution. As a completely new type of solution, we are now introducing a passive UHF RFID-based human-technology interface platform, where the functionality is based on simple on/off inputs. Our platform includes three IC components, each with a unique ID, which are connected to two copper tape dipole antennas. Thus, our platform can be easily integrated into different types of surfaces, such as furniture, items and textiles. The three ICs in the platform provide three push buttons and the possibility of left/right, swiping, all of which can be activated by touching with a finger.

2. PLATFORM DESIGN AND FABRICATION

The design and dimensions of the platform are shown in Figure 1. Our interface platform includes two dipole antennas and three ICs, which act as input buttons. These input buttons are numbered 1–3 from left to right. The antennas and interconnections are manufactured from copper tape, which has glue on the backside, and can thus be easily integrated into the wooden surface. The used ICs are NXP UCODE G2iL RFID microchips (with a wake-up power of $-18\,\mathrm{dBm}$), which the manufacturer has embedded into a plastic film strap structure. This IC strap has two $3 \times 3\,\mathrm{mm}^2$ copper pads, which are used to attach the component to the copper tape conductors. As presented in Figure 1, in our platform, these copper tape conductors are connecting the two copper tape dipole antennas.

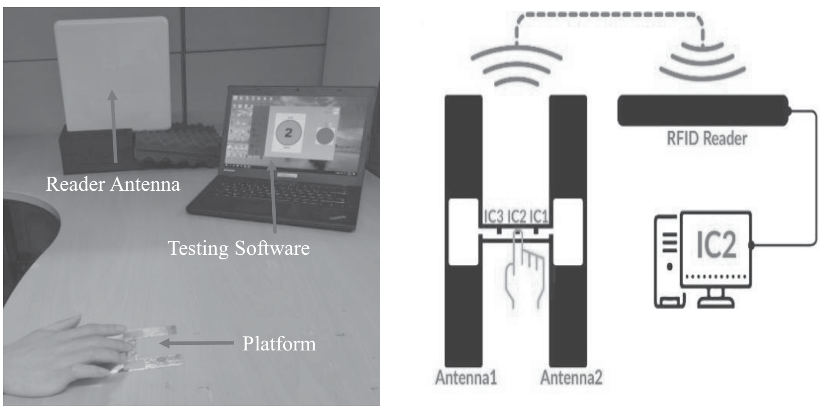


L	*W*	*a*	*b*	*c*	*d*	*e*
120	20	27	16	2	2	43

Figure 1: (a) Platform design with dimensions [mm] and (b) platform integrated into table.

3. PRACTICAL TESTING

Practical testing of our table-integrated user interface is done in a normal office environment. Figure 2 shows the measurement setup, which includes the platform, integrated into the surface of a wooden table, one reader antenna, attached to Thingmagic M6 RFID reader through a connecting cable, and our testing software user interface. The reader operates at the European frequency (865.6–867.6 MHz). The distance between the reader antenna and the table-integrated platform during testing is 90 cm.



(a) (b)

Figure 2: (a) Platform testing setup in an office environment and (b) operating principle of the platform.

The platform is tested by two users, who are given 200 random inputs by our testing software. The software asks the users to perform the following actions in random order: swipe left (i.e., touch buttons 3–1), swipe right (i.e., touch buttons 1–3), touch button 1, touch button 2, touch button 3. Figure 3 shows an example of a situation where the software asks to touch button 2, which is IC 2 in the middle. As shown, the color on the testing software screen is initially blue. When the correct input is detected by the testing software, green color appears on the screen and the software stores the data in an excel sheet as "1". If there is no input during 5 seconds or a wrong input is given, red color appears on the screen and "0" is saved to the excel sheet. The full testing data is gathered into the excel sheet, which stores the asked input, the given input, and the information if the given input was right or wrong, i.e., if it was the same as the asked input.

(a) (b)

Figure 3: (a) Controlling of the user interface platform with finger and (b) testing software screen asking for "button 2" as input.

4. RESULTS AND DISCUSSION

Table 1 shows the testing results for each asked input from the two testers P1 and P2. The overall success rate for P1 and P2 is 98% and 99%, respectively. These preliminary results prove that this table-integrated platform can attain high input accuracy in normal office conditions, despite the challenging wireless environment. Based on these results, our user interface can provide a cost-effective, user-friendly and flexible solution for versatile smart home applications.

Table 1: Initial testing results by two people (P1 and P2).

	Button 1	Button 2	Button 3	Swipe left	Swipe right	All
P1 success rate	100%	99%	100%	100%	99%	98%
P2 success rate	99%	100%	100%	100%	100%	99%

The user interface implemented here requires minimal effort to prepare and deploy and thereby, can be appropriated easily and quickly to various applications. The solution can be easily extended to other flat surfaces, such as walls or doors. Therefore, as long as RFID readers are present in the environment, users can easily administer smart surfaces, such as a touch keypad for opening a child-locked fridge door or a sofa arm that is augmented with an UHF-RFID surface for controlling the level of smart ambient light as well as the television. Simple structure of our system also may make it possible to deploy smart-surface kits that will allow users to craft their own antennas in different form factors with the help of 3D-printers or laser cutters. The number of ICs can also be increased or decreased by users, depending on their preferences on the cost/resolution performance. Possibilities even expand further, when the same structure is extended to uneven surfaces, such as cloth sleeves, which is also part of our future work. These possible applications show that our user interface, by being cost-effective, easy-to-produce and flexible, promises versatile and practical application areas in extensive amount of different contexts.

5. CONCLUSIONS

We introduced a passive UHF RFID-based user interface. Our solution has two copper tape dipole antennas and three passive RFID ICs with a unique ID. This user interface can be used for push button and swipe controlling, as each IC can be activated by touching with finger. Due to the simple design and cost-effective materials, implementation into different types of surfaces is possible. This user interface enables wireless controlling of technology by simple hand movements when sitting by a table. During preliminary testing, 98% and 99% success rates were achieved. These results are very encouraging, especially when considering the versatile application possibilities of the system.

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PUBLICATION V

ClothFace: A Passive RFID-based Human-Technology Interface on a Shirtsleeve

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Research Article

ClothFace: A Passive RFID-Based Human-Technology Interface on a Shirtsleeve

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This paper introduces ClothFace, a shirtsleeve-integrated human-technology interface platform, which comprises two wrist antennas and three radio frequency identification (RFID) integrated circuits (ICs), each with a unique ID. The platform prototype, which is created on a shirtsleeve by cutting the antennas and antenna-IC interconnections from copper tape, can be used for push button and swipe controlling. Each IC can be activated, i.e., electrically connected to the two antennas, by touching the IC. These ICs can act as wireless input buttons to the technology around us. Due to the used passive ultrahigh-frequency (UHF) RFID technology, there is no need for clothing-integrated energy sources, but the interface platform gets all the needed energy from an external RFID reader. The platform prototype was found to be readable with an external RFID reader from all directions at distances of 70–80 cm. Further, seven people giving altogether 1400 inputs tested the prototype sleeves on a table and on body. In these first tests, 96–100% (table) and 92–100% (on-body) success rates were achieved in a gamelike testing setup. Further, the platform was proved to be readable with an off-the-shelf handheld RFID reader from a distance of 40 cm. Based on these initial results, this implementation holds the potential to be used as a touch interface blended into daily clothing, as well as a modular touch-based interaction platform that can be integrated into the surfaces of electronic devices, such as home appliances.

1. Introduction

Technology today allows us to communicate and participate, as well as play games, organize our lives, and learn new things. Digital devices are also rapidly taking a larger role in daily health monitoring, along with their increasing use for supporting exercising, activation, and rehabilitation. However, the current handheld, screen-based, and touch-operated devices are not ideal for all consumers and all use situations [1–3]. For example, lowered cognitive skills, dry fingertips, bad eyesight, and decreased motor skills are preventing the efficient use of digital devices. The available alternatives are usually based on voice or body movement controlling. Voice-controlled interfaces, such as Apple's Siri, Amazon's Alexa, Microsoft Cortana, or Google Assistant, while popular and developing quickly, have their own challenges, such as linguistic coverage and challenges in noisy and strictly noiseless environments. Similarly, there are commercial interfaces that use human body movements, such as Nintendo Wii Remote, Sony PlayStation Move, Jacquard by Google, Kinect from Microsoft, Myo armband from Thalmic Labs, and E-skin sensor shirt from Xenoma. Further, different technologies have been suggested for detecting hand movement on the human body, such as different sensor technologies [4–9] and interactive textiles [10–13]. All the available solutions, however, require a line-of-sight to work, i.e., the gesture maker needs to be directly seen, or an on-board power source, which increases their cost and limits their practical daily use. To overcome these challenges, WIFI signals have been used for gesture monitoring [14–16] but, despite the promising results, these solutions have challenges with multiple user environments and they are only functional in a specific use environment [17].

Passive RFID (radio frequency identification) technology, especially in the UHF (ultrahigh frequency) range, has the potential to become a solution for overcoming the problems mentioned above. Passive RFID uses battery-free, remotely addressable electronic tags, composed only of an antenna and a small RFID IC (integrated circuit) component, having a unique ID. A passive RFID tag gets all its energy from an RFID reader and responds by backscattering. Variations of backscattered signal strengths and phases from body-attached passive RFID tags have been shown to provide information about body positions and movements [18–24]. Further, when a user touches an RFID tag with a finger, the user manifests as a change in phase of the tag's backscattered signal [25, 26]. Moreover, integrating versatile sensing options into passive RFID tags has been done [27–32], and by tracking changes in the tags' backscattered signals, passive UHF RFID tags have been used, for example, as autonomous strain [33–37] and moisture [38–42] sensors. However, despite the promising results, the presented passive RFID tag-based results have shown that the backscattered signals of passive RFID tags are noisy and unstable and strongly affected by the environment. Thus, a new type of approach is needed in order to fully benefit from passive UHF RFID in human-technology interaction.

To satisfy this need, we have developed our ClothFace solution, in which several combined passive RFID IC components are simply "switched on and off" by touch-created electrical interconnections to RFID antennas. Due to the unique ID of each IC, these components can be then used as specific input buttons. Our first passive RFID-based human-technology interaction solution was based on a shirt-integrated antenna, which could be used to activate single RFID IC components placed around the user [43]. Next, we further developed this concept of integrating RFID ICs in the environment around us, by installing a passive RFID-based platform, consisting of three RFID ICs on the surface of the wooden table [44]. Now, in this study, we introduce a new ClothFace concept, a shirtsleeve-integrated touchpad solution, which comprises two wrist antennas and three RFID ICs (each with a unique ID). The interface prototype, which is integrated on a shirtsleeve by cutting the antennas and antenna-IC interconnections from copper tape, can be used for push button and swipe controlling. Each IC can be activated, i.e., electrically connected to the two wrist antennas, by touching with finger. An external RFID reader antenna will provide all the needed energy for the wireless system, which enables the uniqueness of our solution. Our shirtsleeve-integrated interface is fully passive and maintenance-free, having no on-cloth energy sources, which makes fabrication directly into clothing simple and easy, and provides great mobility for practical use. The cost of a basic passive RFID IC is only a few cents, which makes our solution cost-effective and convenient for use in daily clothing. Further, by applying a coating, the platform can be made waterproof and fully washable.

2. Platform Design and Fabrication

The design and dimensions of the platform prototype are shown in Figure 1. Our sleeve interface includes two wrist antennas and three RFID ICs, which act as input buttons. The antenna design is based on our previous paper [43], where we introduced a wrist antenna that had antenna bands going around the wrist. The idea of these antenna bands is that the human wrist will not fully cover the antenna. The bands will go around the wrist, which will provide a better wireless performance and a longer read range. We now combined two of such wrist antennas together and connected the RFID IC components into both. This new type of simple design will allow these three ICs to be readable even when they are not directly facing the RFID reader.

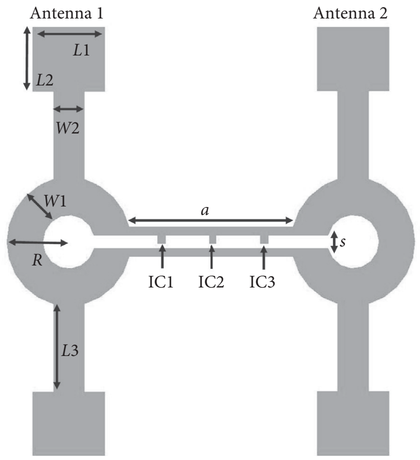
Each RFID IC has a unique ID due to the unique electronic product code (EPC). Based on their EPC codes, the ICs (input buttons) in the sleeve interface are numbered 1–3 from left to right. These prototype antennas and interconnections are manufactured from copper tape, which has glue on the backside, and can thus be easily integrated into the shirtsleeve. The used ICs (shown in Figure 2) are NXP UCODE G2iL RFID microchips (with a wake-up power of −18 dBm), which the manufacturer has embedded into a plastic film strap structure. This IC strap has two $3 \times 3\,mm^2$ copper pads, which are used to attach the component to one of the two copper tape conductors. As presented in Figure 1, in our platform, these two copper tape conductors are connecting the two copper tape wrist antennas.

In this first prototype of the sleeve interface, the ICs are activated using an "input finger" that is a piece of textile (a finger cut from a glove), coated with a copper tape material. Alternatively, the ICs are activated by touching with a bare fingertip. Thus, we are now testing two different methods for further development. When a specific IC strap is touched, the copper tape in the input finger or the bare finger itself will create the needed electrical interconnection from the IC strap pad to the second copper tape line and switch that specific IC readable to the RFID reader.

3. Preliminary Tests

As a preliminary test, the sleeve interface is firstly tested with Thingmagic M6 RFID reader on an office table. The reader operates at the European standard frequency range (865.6–867.6 MHz) and the used power is 28 dBm. The maximum read range of the sleeve interface (the distance from the RFID reader antenna, where the interface is still working flawlessly) is measured from different directions, as presented in Figure 3. Further, the backscattered power for each IC on the sleeve is recorded at the maximum distance. As can be seen from Table 1, the sleeve works from all directions from distances of 70–80 cm, which is a good starting point.

Next, the on-body performance of the sleeve interface is tested in an office environment with a handheld mobile RFID reader. In order to evaluate the practical potential of the sleeve, it is tested on a male subject (as presented in



L1	L2	L3	W1	W2	R	s	a
36	30	39	16	16	30	6.5	40

Figure 1: Platform design with dimensions (mm).

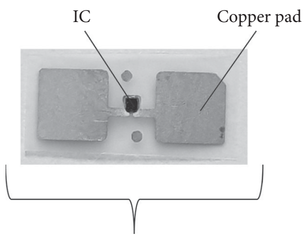


Figure 2: RFID IC strap used as an input button.

Figure 3) and the maximum read range is measured. The reader (Nordic ID Medea) operates at 866 MHz. The three ICs on the sleeve operate efficiently at 40 cm from the mobile reader.

4. Practical Test

As presented in Figure 4, the sleeve interface is tested while placed on a wooden table (meaning without the effects of the human body) and while worn on body (where the lossy human body as well as body movement may affect the antenna performance). The sleeve interface is tested by seven users (three females and four males), who are each asked to give 200 random inputs by our gamelike testing software. Four of the users test the interface with the input finger, while three of them test the interface with a bare finger. By using both methods, only a gentle touch is needed to activate the ICs.

Figure 5 shows the measurement setup, which includes the interface platform, integrated into a sleeve of a cotton shirt, one circularly polarized reader antenna, attached to Thingmagic M6 RFID reader through a connecting cable, and our testing software user interface. The practical testing of our sleeve interface is done in a normal office environment with wooden and metallic furniture, people, and computers. The wireless environment in the office is also in a normal condition, meaning that mobile phones are used and there is also an indoor WIFI signal. As shown in Figure 4, the reader antenna was placed directly opposite to the wrist antennas on the table, while it was facing the wrist antennas at a 90-degree angle when the interface was tested on body. The goal was to get a better understanding of the practical use possibilities.

Figure 6 shows an example of a situation, where the software asks the user to touch button 3, and the user is controlling the platform with a bare finger. Further, in Figure 7, the software asks the user to swipe right, and the user is controlling the platform with the input finger. The testing software is developed on the Net framework with C# as windows forms application. The testing software uses ThingMagic Mercury API tools to control the M6 reader and filter received RFID tag IDs to focus only on the ICs on the test (and not to be disturbed by any surrounding RFID tags). The ThingMagic Mercury API supports continuous reading, so it was chosen to retrieve RFID tags from the M6 reader. The testing software asks the users to perform the following actions in random order: swipe left (i.e., touch buttons 3–1), swipe right (i.e., touch buttons 1–3), touch button 1, touch button 2, and touch button 3.

During testing, the system stores the asked input, the given input, and the information if the given input was the same as the asked input. As shown in Figure 6, the color on the testing software screen is initially blue. When the correct input is detected by the testing software, green color appears on the screen and the software stores the data as “1”. If there is no input for 5 seconds or a wrong input is given, red color appears on the screen and “0” is saved.

Table 2 shows the testing results from the four testers, who use the interface with the input fingers, while Table 3 presents the results from the three users, who use the platform with their bare fingers. The overall success rate for the table and arm setup is 96–100% and 92–100%, respectively. These preliminary results prove that this sleeve-integrated platform can attain high input accuracy in normal office conditions, despite the challenging wireless environment. The performance seems to be equally good on a table and on body, which supports the use of our novel wearable platform design having two wrist antennas attached to the ICs. There is no significant difference between the results achieved with the input finger and a bare finger. The results from table measurements with a bare finger and with the input finger are 96–99% and 96–100%, respectively, while the on-body results are 92–97% and 97–100%, respectively. Based on these results, it is possible to control the ClothFace interface with a bare finger, which removes the need for a specific input finger and provides more flexibility for practical use. Thus, the development of the next prototype will focus on using the platform with a bare finger.

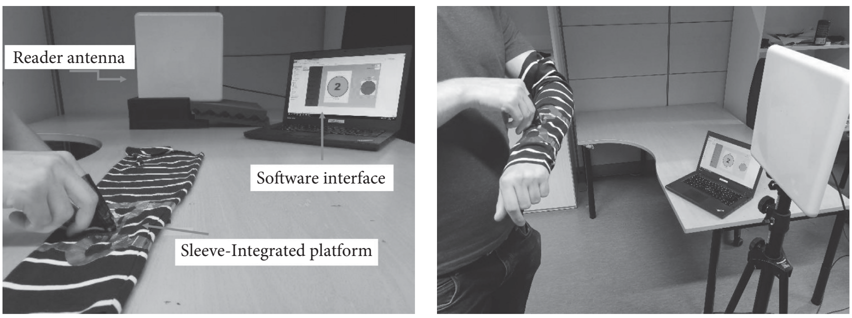
As can be seen from Figures 6 and 7, the sleeve interface may get crumpled when used. This may result in unwanted inputs and wanted inputs being ignored by the system. This

(a) (b)

Figure 3: (a) Platform testing with a mobile reader and (b) M6 reader.

Table 1: Preliminary testing results with the M6 RFID reader.

Direction 1 (*D*1)				Direction 2 (*D*2)				Direction 3 (*D*3)				Direction 4 (*D*4)			
Read range (cm)	Backscattered power (dBm)			Read range (cm)	Backscattered power (dBm)			Read range (cm)	Backscattered power (dBm)			Read range (cm)	Backscattered power (dBm)		
	IC1	IC2	IC3		IC1	IC2	IC3		IC1	IC2	IC3		IC1	IC2	IC3
75	−51	−50	−52	75	−43	−43	−48	80	−55	−56	−55	70	−46	−46	−47



(a) (b)

Figure 4: (a) Platform testing setup on a table and (b) on body.

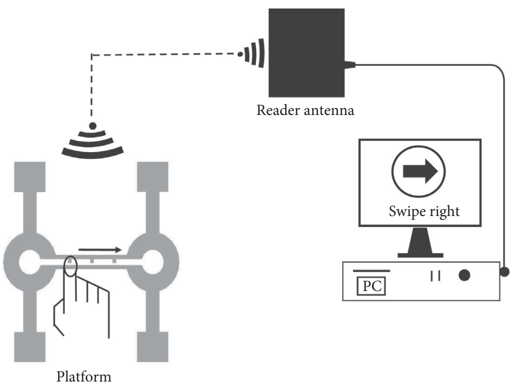
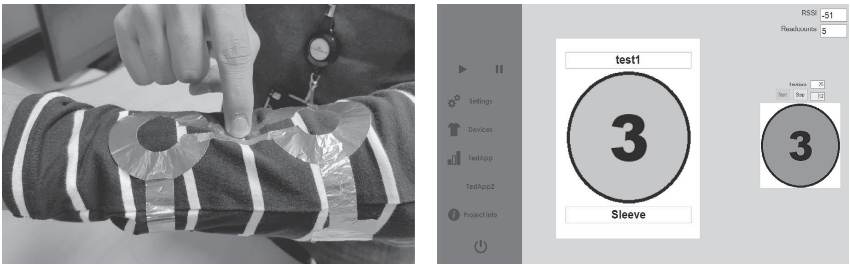
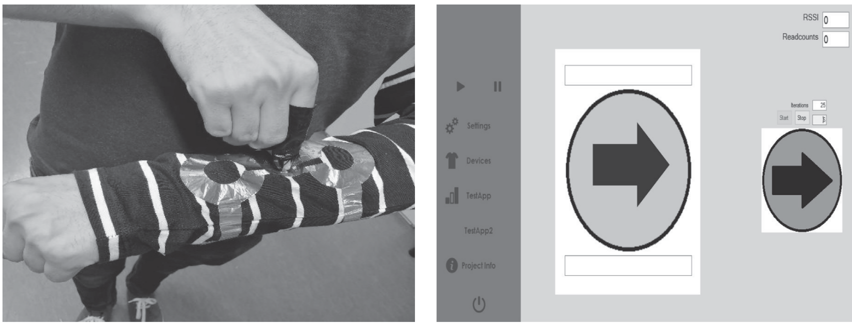


Figure 5: The operating principle of ClothFace sleeve.



(a) (b)

Figure 6: (a) Controlling of the sleeve platform with a bare finger and (b) testing software screen asking for “button 3” as input.



(a) (b)

Figure 7: (a) Controlling of the sleeve platform with input finger and (b) testing software screen asking for “swipe right” as input.

Table 2: Initial testing results by four people (input finger).

Subject	Female 1		Female 2		Male 1		Male 2	
	Table (%)	Arm (%)	Table (%)	Arm (%)	Table (%)	Arm (%)	Table (%)	Arm (%)
Success	99	99	100	98	96	97	98	100
Error	1	1	0	2	4	3	2	0

Table 3: Initial testing results by three people (bare finger).

Subject	Female 3		Male 3		Male 4	
	Table (%)	Arm (%)	Table (%)	Arm (%)	Table (%)	Arm (%)
Success	96	97	98	92	99	95
Error	4	3	2	8	1	5

did not occur during any of the tests but needs to be considered in the future. Thus, our plan is to fabricate the next prototype from electrotextiles, which blend into clothing better than the copper tape. Further, we trust that a protective coating will also help with the abovementioned challenge.

Previous projects, such as Google Jacquard [10], also provide similar interaction modalities; however, due to their complex structures and components, they need specifically designed clothes preventing the variety in terms of aesthetics and functionality. On the contrary, our implementation promises versatility in terms of visual aesthetics, interaction resolution and area, and broad opportunities for customization to different uses and contexts. The fundamental strength of the user interface implemented here lies within its passive nature, cost-effectiveness, and simple implementation into clothes.

It is not hard to imagine rapidly deploying ClothFace to different types of clothing, such as pants, gloves, or hats. This versatility can suggest using our system as a platform for implementing and testing many speculative on-body gesture design studies, such as [45, 46]. Moreover, although antennas and the circuit can be concealed beneath the cloth, the form factor of the current implementation also hints fashion design studies that can help to create a new visual language for RFID-based smart clothing, which can leave copper parts visible by incorporating diverse visual interpretations. The results achieved with the handheld mobile reader support our future goal to study using such interfaces with mobile phone-integrated UHF RFID readers. If mobile phones widely adopt UHF RFID readers, clothes can be designed for different functions in various forms. For example, we can produce a diverse array of gaming t-shirts representing distinct game characters. Easy deployment of our system can facilitate producing different types of input commands that can be used on various parts of the body for controlling games. This would create unique player experiences for different characters according to their special abilities in a game and would be a worthy contribution to the emerging gaming wearable area [47, 48]. This versatility can also be expanded into daily life tasks, such as kitchen-aprons interacting with the house while preparing a meal or pajamas giving access to the control of TV and the music system. Our solution can give special groups, such as disabled people with different limitations and elderly people with bad eyesight and memory, more possibilities for independent living. Further and more detailed implementations of this system will also make exploring body-related interactions in a rapid way possible, which can yield a platform for design research in areas such as Somesthetic Design [49]. These speculative ideas demonstrate that the virility of our implementation and our further work encapsulate exploring these distinct dimensions.

In this direction, our next step as further work is to create a wearable prototype, which can be comfortably used for daily life actions. The sleeve platform will be embedded between two layers of cotton textiles. The copper tape lines and the RFID IC strap pads inside will be separated by a thin textile net, which means that they will form a contact when the surface of the top layer textile is touched. This will remove the need for a specific input finger and integrate the platform seamlessly into the shirtsleeve.

5. Conclusions

We introduced a ClothFace sleeve, a passive UHF RFID-based human-technology interface, integrated into a sleeve of a cotton shirt. The created textile touchpad enables push button and swipe controlling without on-cloth energy sources. During practical testing, 96–100% and 92–100% success rates were achieved on a table and on body, respectively. These results are very encouraging, especially when considering that the sleeve interface, being cost-effective and flexible, promises versatile and practical application areas in an extensive number of different contexts. As these preliminary results seem to suggest that it is possible to control the platform with a bare finger, the next prototype will be developed to be controlled without an input finger, which will make it more flexible and more suitable for practical use. More, the prototype will be further developed by seamlessly integrating it into clothing. The next goals are to make the platform smaller in size, optimize the antenna design for longer read ranges, and test different coating materials to achieve washability. Due to the promising results achieved with the handheld mobile reader, our plan is to start tests with mobile phone-integrated UHF RFID readers, which can be held in a pocket for a truly mobile system. We imagine that this type of clothing-integrated user interface opens possibilities especially for special needs groups, such as people using alternative and assistive communication technologies. By using individually tailored mobile phone applications, these people could benefit from versatile “communication clothes” in their daily lives.

Data Availability

The measurement data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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PUBLICATION VI

ClothFace: A Batteryless Glove-Integrated User Interface Solution based on Passive UHF RFID Technology

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ClothFace: A Batteryless Glove-Integrated User Interface Solution based on Passive UHF RFID Technology

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***Abstract*— Due to their unique advantages, wearable user interface solutions have gained a lot of research and commercial interest. This paper introduces ClothFace technology by presenting a batteryless glove-integrated user interface. The solution is based on passive ultrahigh frequency (UHF) radio frequency identification (RFID) technology. The first prototype of this solution was fabricated from copper tape to a normal cotton-based glove. The user interface on the glove consists of three antenna parts on three different fingers of the glove, each of which has an RFID microchip with a unique ID. Further, an additional antenna part is attached to the thumb of the glove. The antennas are initially separated from each other, and none of the microchips is readable for the RFID reader. When thumb antenna touches any of the three finger antennas, the touch creates an electrical connection, and the corresponding microchip can be detected by the RFID reader. In this study, the developed glove-integrated user interface was evaluated in an office environment by three test subjects, who all received 100 orders from a specific testing software. The average success rate in this first test was 98 %. These initial results are very encouraging, especially when considering that the glove-integrated user interface, being light, flexible, and cost-effective, promises versatile interesting applications in several fields.**

Keywords—antennas, glove, intelligent clothing, passive UHF RFID, user interface, textile electronics, wearables, wireless systems.

I. INTRODUCTION

In recent attractive human-technology interaction solutions, wearable systems have been used as user interfaces through touch or human body movement. The most common ones of such interfaces, for example touchpads and tapping buttons [1]-[4], can be integrated around the arm for detecting hand movements. This type of placement is very convenient for practical use.

Several different types of technology solutions have been developed for wearable touch and gesture recognition systems, such as skin electronics [5], versatile sensors (for example acoustic, ultrasonic, infrared proximity, and reflective marker sensors) [1]-[6], and interactive textiles [7][8]. The main challenge, when considering their daily use and maintenance, is that most of these solutions require complex electronics together with an on-board power source. These requirements significantly increase their cost and limit their flexibility and functionality in practical use.

Further, different vision-based methods have been presented to capture touch traces on surfaces. This is enabled by using several cameras [9]-[11]. As a line-of-sight from the cameras to the user is needed, which means the user must be directly seen by the cameras in these solutions, their usability and especially mobility is quite limited. By using normal WIFI signals, namely by measuring the received signal strength indicator or channel state information, promising early results have been achieved in recognizing different types of gestures and in using them as digital inputs [12][13]. However, WIFI solutions are used in specific environments, and they are challenging to establish into multiple user environments [14].

The properties of passive ultra-high frequency (UHF) radio frequency identification (RFID) technology make it an attractive solution for wearable user interfaces. Passive UHF RFID tags communicate wirelessly with RFID readers, and they have a working range of several meters. Each RFID tag has a microchip, i.e., RFID integrated circuit (IC), which has a unique ID. As this technology is fully passive, it does not require any on-board power source. Instead, the tags are powered directly by the reader. The tags respond to the reader by backscattering the received signal with their unique ID. When passive UHF RFID tags are attached to the human body, body movement will cause a variation to the backscattered signal. The variations of the backscattered signal strengths and phases have been successfully tracked in order to recognize specific body positions and movements [15]-[17]. Further, different sensing properties, such as temperature sensing, have been integrated into RFID microchips. Finally, as a change in the antenna length or wetting of the antenna substrate both affect the backscattered signal of a passive UHF RFID tag, by tracking the changes in the tags' backscattered signals, passive UHF RFID tags themselves have been also used for example as strain and moisture sensors [18]-[20].

However, despite the successful versatile use of passive UHF RFID technology presented above, passive RFID tag-based gesture tracking and sensor results have revealed, that the backscattered signals of passive UHF RFID tags in normal use environments are noisy and unstable. Thus, a new type of approach is needed in order to fully benefit from this cost-effective and simple technology.

A so called "ClothFace technology" has been developed to solve the above-mentioned challenges. ClothFace enables a simpler readable/non-readable use of RFID microchips, which means the functionality can be simply on/off. The first ClothFace solution, i.e., a clothing-integrated passive UHF RFID human-technology interaction solution, was based on a shirt-integrated antenna, which could be used to activate single RFID microchip components placed around the user [21]. Next, this concept was developed further by fixing a passive RFID-based table platform, consisting of three RFID microchips [22]. Here, several combined passive UHF RFID microchips could be "switched on and off" by touch-created electrical interconnections to antennas. Due to the previously mentioned unique ID of each microchip, they could be then used as specific input buttons.

In this paper, the ClothFace technology is developed further. We are establishing a glove-integrated user interface solution, which comprises of four antenna parts and three RFID microchips (each with a unique ID). A specific microchip, and thus a specific ID, can be activated by single finger movements, and then used as a digital input. Further, swipe controlling to left and right can be achieved easily by only slightly more complex finger movements. As our passive UHF RFID technology-based solution is completely self-energy efficient and draws all the needed power from an external RFID reader, the glove itself is extremely light and flexible.

The used antenna designs are next introduced in the second chapter. The chapter also introduces the design and manufacturing of the glove-integrated interface solution. This developed user interface is tested in the third chapter. The results of the testing are presented in the fourth chapter. The fourth chapter also discusses the practical use of the solution and its potential application areas. Finally, the conclusions of this study are presented in the last chapter.

II. Antenna and Glove-Integrated User Interface Designs

The design of the developed two-part passive UHF RFID antenna is illustrated in Fig. 1. For the glove-integrated user interface, three of such antennas were used. The antennas were integrated into a normal cotton-based glove. As shown in Fig. 1, the antenna was separated into two parts. Part A has an attached UHF RFID microchip. Part A antennas were firstly attached on the index finger, the middle finger, and the little finger on the glove. Part B of the antenna was then attached on the thumb of the glove.

All the antenna parts for this first prototype were cut from a non-stretchable copper tape. All the antennas and the microchip components were attached to the glove using normal textile glue. The microchip used in this work belongs to NXP UCODE G2iL RFID microchips. It has a wake-up power of −18 dBm (15.8 µW). These components were connected to the antennas (to Part A) by conductive epoxy glue (Circuit Works CW2400). A ready-made glove-integrated user interface solution is presented in Fig. 2.

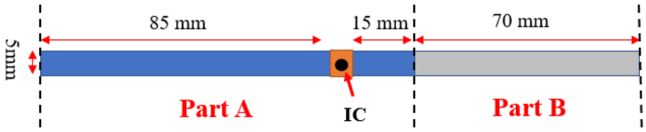

Fig. 1. Glove-integrated user interface antenna design with dimensions.

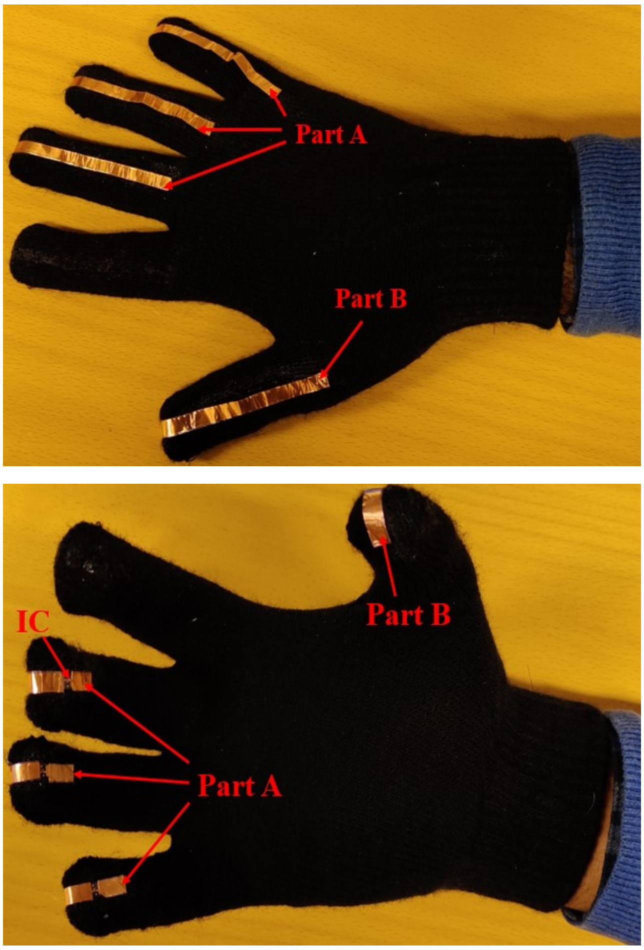

Fig. 2. Top side of the glove (top) and palm side of the glove (bottom).

As presented in Fig. 2, the two parts of the antenna were initially disconnected. Thus, none of the microchips were readable for the external RFID reader. This off-status of the platform is also shown in Fig. 3. When the thumb antenna touches any of the other three antenna parts in fingers, the touch creates an electrical connection between Part A and Part B of the antenna. Thus, the corresponding microchip can be detected by the RFID reader. This microchip activation is shown in Fig. 3. During user interface development, it was discovered that a good alignment of Part A and Part B is needed for activation of the microchip, which is a key design aspect in this glove.

III. TESTING SETUP AND TESTING SOFTWARE

Fig. 4 shows the testing setup, which included the glove-integrated user interface, a circularly polarized RFID reader antenna, which was attached to Thingmagic M6 RFID reader through a connecting cable, and a specific testing software. The reader operated at the European standard frequency range (865.6-867.6 MHz) and the used power was 28 dBm. All wireless testing was performed at 70 cm from the RFID reader antenna. At this distance, the glove interface was found to have an optimized wireless performance.

As presented in Fig. 4, the testing setup was built to a normal office environment. Thus, the testing environment was very realistic, when considering for example practical use in a home environment, which also has wooden and metallic furniture, as well as people walking around using their mobile phones and WIFI.

The testing software, which is presented in Fig. 5, has been described with more details in a previous study [22]. The testing software uses ThingMagic Mercury API tools to control the M6 RFID reader and filters the received microchip IDs, so that no other RFID tags around will disturb the system performance.

Fig. 3. Off-status (top) and on-status (bottom) of the glove-integrated user interface.

One female and two male test subjects participated in the glove-integrated user interface testing. All the initial test users were familiar with the solution concept before testing it. The testing software asked the users to perform the following actions in a random order: touch finger 1, touch finger 2, touch finger 3, swipe left (done by touching fingers 3 to 1), swipe right (done by touching fingers 1 to 3). Each tester received 100 orders, and the testing software saved the inputs given into an excel sheet. The results were saved in a right/wrong format, which was presented as 1/0, respectively. The testing software also stored the asked input and the given input. If there was no input given within 5 seconds, the input was saved as a 0 and thus also counted as an error.

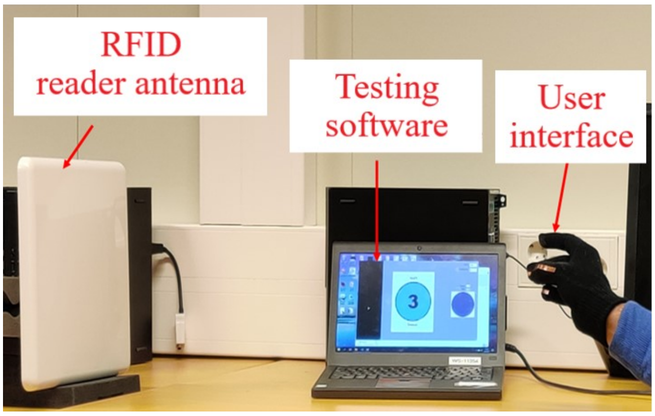

Fig. 4. Testing setup and testing software in an office environment.

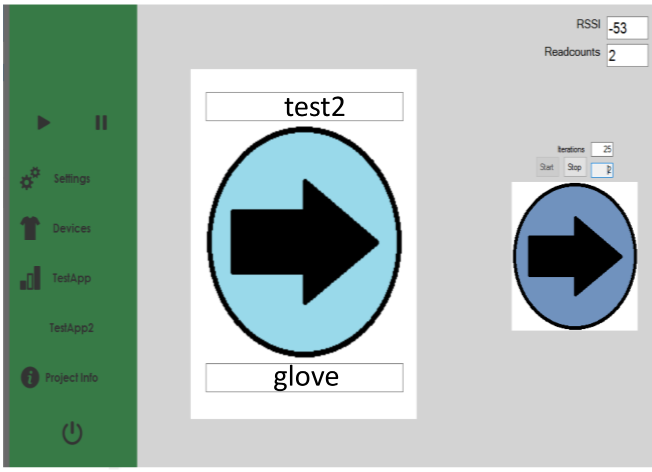

Fig. 5. Testing software screen asking for “swipe right” as an input.

IV. RESULTS AND DISCUSSION

Table I shows the testing results from three testers, who all received 100 orders from the testing software. As can be seen, the overall success rate in this first test was 98 %. Thus, these preliminary results prove that the glove-integrated user interface can attain a high input accuracy in a normal office environment, which is quite like a home environment.

TABLE I. SUCCESS AND ERROR RATES OF THE THREE TESTERS USING THE GLOVE-INTEGRATED USER INTERFACE IN AN OFFICE ENVIRONMENT.

Tester	Success rate	Error rate
1	98%	2%
2	99%	1%
3	98%	2%

These first results about transferring ClothFace technology into gloves can be considered promising. The fundamental strengths of the glove-integrated user interface implemented here lie within its passive nature and cost-effective and simple implementation into clothes. This glove interface uses simple finger movements, which makes it extremely simple to use and thus also convenient for children and elderly people.

This type of intelligent gloves could be used to improve work efficiently and safely, for example in replacing paper and pen by using hand gestures for writing simple notes, or by accessing doors and storages by giving the right password with one's work glove. We also imagine the glove-integrated solutions to be useful in entertaining games as well as in gamification of learning and therapy. A light glove could replace the traditional heavy game controllers, and thus especially support gaming of people who have decreased hand strengths. Further, we imagine this glove to make educational and rehabilitation games more fun, which will greatly support learning and therapy. For example, physiotherapy games could use the glove together with RFID solutions integrated into other parts of one's clothing or into the surroundings. Finally, we imagine this glove to enable more communication possibilities for people with speech and language problems. With the help of our user interface and personally designed software, people could express themselves, for example by writing sentences or by asking for help. This could provide more autonomy and independence.

As a next step, we are optimizing the antenna designs used in the glove. Our goal is to make the user interface functional in the whole office room by using as few reader antennas as possible. Further, we are testing different types of manufacturing methods to integrate the antennas into different types of gloves. Possible methods and materials include for example electro-textiles and embroidery with conductive thread. All these possibilities are cost-effective, as is the whole solution: The cost of a microchip is a few cents, whereas the antennas can be fabricated by costs less than a dollar. The M6 reader and antennas are available in the market for around 1000 dollars.

Further, our goal is to use the glove with a mobile phone-integrated UHF RFID reader. When compared to the M6 reader, it is cheaper and comes handy due to the portability. This will make the system fully mobile, as it is powered and controlled through the mobile phone. Further, the glove-integrated user interface will be able to take advantage of any auxiliary or external technology, which can be connected to the system through the mobile phone's Bluetooth connection.

In the future, we want to use the ClothFace technology to build versatile clothing-integrated wireless platforms, which look and feel like normal clothing, and can be comfortably used in the daily life actions. As discussed, such clothing-integrated user interfaces have countless of applications. Our plan is to explore especially the possibilities of our glove in development of novel communication possibilities for people with speech and language problems.

V. CONCLUSION

In this paper, we introduced a new application of the ClothFace technology, a passive UHF RFID-based user interface, integrated into a glove. The presented first prototype was fabricated from copper tape into a normal cotton-based glove. During preliminary testing, an average success rate of 98 % was achieved by three testers in an office environment. These results are very encouraging, especially when considering that the glove-integrated user interface, being cost-effective, light, and flexible, promises versatile applications in several fields.

Next, the glove-integrated user interface solution will be further developed by optimizing the antenna designs for the best possible wireless performance. Further, we will be testing different types of antenna materials and glove types, as well as taking advantage of mobile phone-integrated UHF RFID readers, which will provide a full mobility and more application possibilities for the system.

ACKNOWLEDGMENT

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PUBLICATION VII

Development, Fabrication and Evaluation of Passive Interface Gloves

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Development, fabrication and evaluation of passive interface gloves

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Abstract

Previously, glove-integrated communication based on gestures, hand movement and finger touch had a complex operating system and an active power source was needed. This paper introduces batteryless and maintenance-free interface gloves. Our solution is based on passive ultra-high frequency (UHF) radio frequency identification (RFID) technology, comprising four electro-textile antenna parts and three RFID microchips (each with a unique ID). The three RFID microchips have unique IDs, which can be activated by the gentle touch of the human finger and used to control the surrounding technology. The aim is to evaluate the reliability of different conductive materials and microchip attachment methods. The antennas are fabricated from two different materials: a stretchable and a non-stretchable commercial electro-textile. Further, two types of microchip attachment methods are used with both antenna materials: a conductive silver epoxy and embroidery with conductive multifilament silver-plated thread. The developed interface gloves are tested by six users in a home and in an office environment, where they achieve 93–100% success rates. Especially those glove interfaces with the antennas fabricated from the non-stretchable electro-textile and the antenna-microchip interconnections embroidered with conductive thread showed good read ranges (80–110 cm). The gloves also show practical functionality, when tested with a mobile reader in practical identification and access control application. These results are very encouraging, especially when considering that the interface glove, being maintenance-free and cost-effective, promises versatile and interesting applications for customizing user-friendly augmentative and alternative communication solutions, easy controlling of ambient assisted-living applications, and providing simple identification and access control for increased safety and comfort.

Keywords

Antennas, glove, electro-textiles, intelligent clothing, passive UHF RFID, user interface, textile electronics, wearables, wireless systems, augmentative and alternative communication, AAC, fingerspelling recognition

Speech and communication problems are widespread. Alternative and Augmentative Communication (AAC) refers to supplement or replacement of spoken communication for people who cannot communicate by speaking. The currently used high-tech AAC solutions can be grouped as follows: eye-gazing or tracing and head-pointing systems, touch-activated systems, breath-activated systems, and mechanical or electromechanical systems.[1,2] Furthermore, noninvasive and invasive brain–computer interface solutions are constantly being developed, since those solutions might allow AAC users to control external devices by modulating their brain signals.[3–5] Despite the versatile solutions, several user groups have difficulties accessing the currently available high-tech AAC solutions, which are often restrictive for users who are physically or cognitively impaired.[2,6] Thus, even better solutions are needed.

For instance, with an interface glove, physically impaired users with voluntary finger movement could operate devices and ambient assisted-living

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applications, such as lighting and "call for help" requests. By converting hand gestures using the sign language alphabet to speech and/or text, the technology would lower the communication barrier between the hearing-impaired and hearing people. Further, an interface glove could provide simple identification and access control without keys or ID cards, which would increase comfort and safety. In previous studies, there have been interesting glove-integrated communication systems, such as a tactile sensing glove system designed to interact wirelessly with the surroundings,[7] a wearable tactile interface based on finger Braille[8] and a communication solution for deafblind people through a smart finger Braille glove.[9] Further solutions include a communication glove with wireless sensors to detect different finger gestures,[10] an interpreter glove for people with speech impairment disability through an audible speech-producing software,[11] an intelligent glove for deaf and mute people,[12] a hand-gestures-translated-into-speech glove solution,[13] and finally, for visually impaired people, a hand Braille glove.[14] All the above introduced gloves, while being successful solutions, have a complex operating system, and an active power source is needed for their operation, which means they require maintenance that limits their practical functionality. Further, due to the complex electronics needed, they are quite costly.

When integrated into gloves as an "interface glove," passive radio frequency identification (RFID) technology also enables customized AAC and environment-controlling solutions to address the needs of various users. Recently, passive RFID-based systems have been installed into footwear and into different types of gloves, for example, for activity monitoring, interactive learning, and for assisting in routine work tasks.[15–18] The properties of passive ultra-high frequency (UHF) RFID technology make it an especially attractive solution to be seamlessly integrated into clothing. Passive UHF RFID tags communicate wirelessly with RFID readers, and they have a working range of several meters. Each RFID tag has a microchip, that is, an RFID integrated circuit (IC), which has a unique ID. As this technology is fully passive, it does not require any onboard power source. Instead, the tags are powered directly by the reader, which can be an external reader or integrated into a mobile phone. The tags respond to the reader by backscattering the received signal with their unique ID.

Now, we are establishing an interface glove solution, which comprises four electro-textile antenna parts and three RFID microchips (each with a unique ID). A specific microchip, and thus a specific ID, can be activated by simple finger movements, and then used as a digital input. Our passive UHF RFID technology-based solution draws all its needed power from an RFID reader, and the glove itself is extremely light and flexible. RFID tag antennas have been successfully integrated into different types of gloves for identification and access control.[19,20] Further, the first prototype of an interface glove[21] had a success rate of 98% in an office environment. However, as the prototype was fabricated from copper tape, it was not a textile-based flexible solution, and thus not suitable for practical use. Further, the design was not optimized to be used near the human body. The main advantage of the solution presented in this paper is its passive nature: There is no need for a battery in the glove. Further, the cost of an RFID IC is only a few cents, which makes the glove very cost-effective. In this paper, the objective is to evaluate the usability of different electro-textile materials and microchip attachment methods. We study fully textile-based battery-free interface gloves, present the new system design and the fabrication methods and materials used, test the fabricated interface gloves in two different environments with a fixed RFID reader and a mobile RFID reader, and evaluate the interface glove's read ranges in practical use situations.

Interface glove

The design of the developed two-part passive UHF RFID antenna is illustrated in Figure 1. Compared with the first version, presented elsewhere,[21] the antenna length of both parts is similar, in order to improve the read range of the glove-integrated tags. The antennas were integrated into a normal cotton-based glove. As shown in Figure 1, the antenna was separated into two parts, where Part A has an attached UHF RFID microchip, and they were firstly attached on the middle

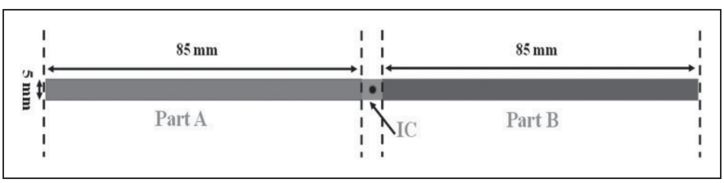

Figure 1. Antenna design with dimensions.

finger, ring finger, and the little finger on the glove, as presented in Figure 2. Part B of the antenna was then attached on the thumb of the glove only, as presented in Figure 2. The index finger is left unused because we only targeted three inputs from the user in this study, but adding another IC would be straightforward.

The tag antennas integrated into gloves were fabricated from two different conductive textile materials. The properties of both materials are presented in Table 1. The tag antennas for the first type of glove were fabricated from a stretchable electro-textile (Less EMF stretch conductive fabric, presented in Figure 3), and the tag antennas for the second type of glove from a non-stretchable electro-textile (Less EMF Shieldit Super fabric, presented in Figure 4). The silver-based stretchable electro-textile is Less EMF stretch conductive fabric (Cat. #A321), with a thickness of 0.4 mm and a sheet resistance less than 1 ohm/square. According to the manufacturer, this material can be stretched to a maximum of 200%. The non-stretchable electro-textile, nickel-plated Less EMF Shieldit super fabric (Cat. #A1220), has a thickness of 0.17 mm and a sheet resistance of 0.07 ohm/square. Both antenna materials were attached to the gloves with normal textile glue. We used a NuSil MED-2000 adhesive silicone. This glue is one part solvent-free silicone. The adhesion property is good, and it remains flexible after applying on the substrate. The stretchable electro-textile is conductive from both sides, while the non-stretchable electro-textile material has only one conductive side, which was attached to the glove with the textile glue.

Further, two types of IC attachment methods were used in both antenna materials: The ICs were attached to the antennas either with a conductive silver epoxy (Circuit Works CW2400) or by sewing with a conductive multifilament silver-plated thread (Shieldex multifilament thread 110f34 dtex 2-ply HC), which has a resistance of 500 ± 100 Ω/m and a diameter of 0.16 mm. The IC (NXP UCODE G2iL RFID IC) has conductive copper pads for simple attachment, as shown in Figure 5 and Figure 6. The wake-up power of the IC is -18 dBm (15.8 μW). The ready interface gloves are shown in Figures 5 and 6.

The tag antennas have two parts (A and B). The tag antennas were initially not readable because the two parts of the tag antennas (A and B) were not connected, which means none of the ICs were readable by RFID readers. When the B part of the tag antenna glued on the thumb of the glove touches any of the other three antenna parts (the conductive pads of the ICs) attached to the fingers of the glove, the touch creates an electrical connection between Part A (IC pad) and Part B of the tag antenna. If the tag antenna Part B touches the IC pad on the tag antenna Part A, the IC can be activated with a simple and gentle touch of the fingertip. Thus, the corresponding IC can be detected by RFID readers and recorded as an input for any desired application.

Test setups

The system evaluation setup included the glove interface, a circularly polarized RFID reader antenna, which was attached to a ThingMagic M6 RFID reader through a connecting cable, and specific testing software. The reader operates at the European standard frequency range (865.6–867.6 MHz) and the power used was 28 dBm.

The testing software was initially developed for evaluation of a table-integrated passive RFID system and has been described with details elsewhere.[24] It uses ThingMagic Mercury API tools to control the M6 RFID reader and filters the received microchip IDs, so that no other RFID tags nearby will disturb the performance of testing software. The software shows random orders (1,2,3) on the screen of a computer and the user responds to the ordered input by touching

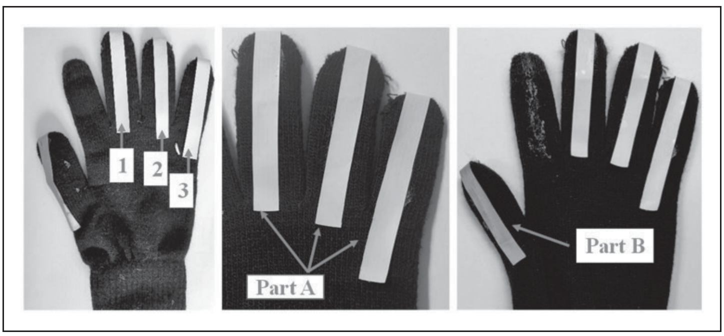

Figure 2. Top side of the interface glove (fabricated from non-stretchable electro-textile) showing also the number of each finger (left) and antenna parts (A and B) integrated in fingers and thumb, respectively (middle and right).

Table 1. Properties of stretchable and non-stretchable electro-textile materials

Material	Commercial name	Properties Thickness	Weight	Resistivity	Color	Base	Conductor	Price	Stretch
Stretchable electro-textile (knitted)[22]	Less EMF Stretch Conductive Fabric	0.40 mm	4.3 oz/yd^2	<1 Ohm/square (unstretched)	Brown	76% nylon, 24% elastic fiber	Silver-plated	$ 3100 per roll (100 lin ft roll)	~100% in length, ~65% in width
Non-stretchable electro-textile (woven)[23]	Less EMF Shieldit Super Fabric	0.17 mm	6.784 oz/yd^2	<0.07 Ohm/square	Gray	Polyester/hot melt adhesive on the backside	Nickel- and copper-plated	$670 per roll (100 lin ft roll)	–

the fingers (1,2,3) respectively. If the ordered input is returned correctly by the user, a green circle appears on the screen. Otherwise, a red circle shows that a wrong output has been saved. The outputs are saved as (1) for a right input and (0) for a wrong input in an Excel sheet.

Two female and four male test subjects participated in the evaluation of the developed interface gloves, which were tested in a home and in an office environment. The participants were selected from two groups: (1) people who are familiar with the glove interface technology (our colleagues from the university) and (2) people who are not familiar with the glove interface technology (also our colleagues from the university). Further, the glove interfaces were tested in a home environment and in an office environment (tested by our colleagues from the university, all of them familiar with the glove interface). The aim is to measure the read ranges and evaluate the success rates of the interface gloves manufactured from different materials. Out of the six people, four were familiar with the system, while two were new to the system. First, each person measured the maximum read range for the glove, which is the read range where the glove still showed reliable performance. For evaluation, each tester received 100 random orders (order 1, 2, or 3: meaning touch finger 1, 2, or 3 with thumb, respectively, as presented in Figure 2) from the testing software. The results were saved in a right/wrong format. If there was no input given within 5 s, the input was also counted as an error. A random test setup in a home environment is shown in Figure 7. As can be seen, the environment is very open and there is no furniture near the measurement setup. Further, there were only the test subject and the assisting researcher present during the measurements. A random measurement setup in an office is shown in Figure 8. As shown, there are electronic items including laptops and mobile phones close by. There are metallic and wooden furniture and people are moving around constantly.

Our goal is to make the system fully mobile, which requires a mobile RFID reader. Thus, in order to evaluate the read range of the glove for practical future applications, the read range was measured in both environments using a handheld RFID reader (Nordic ID Medea), as presented in Figures 7 and 8. These measurements were carried out by three people. The reader measures the tags at 866 MHz, which is the European center frequency for UHF RFID systems, and then communicates with any background system though Wi-Fi. As the reader is handheld and thus mobile, this user interface can be easily transferred together with the person using it.

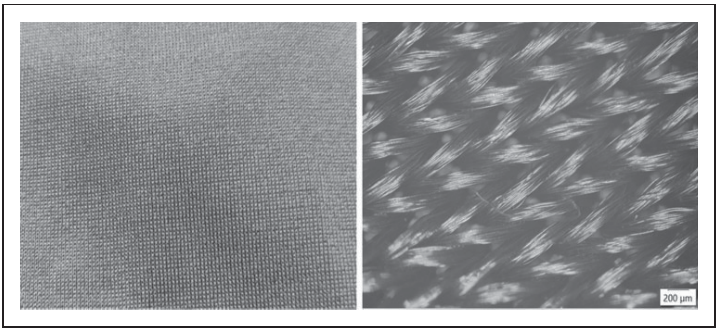

Figure 3. Stretchable electro-textile in a picture (left) and in a microscopic view (right).

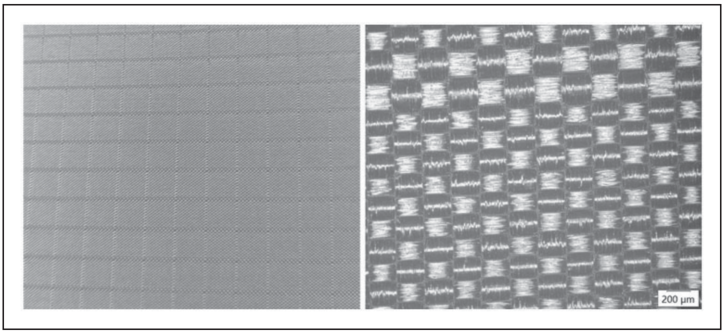

Figure 4. Non-stretchable electro-textile in a picture (left) and in a microscopic view (right).

Results and discussion

A read range threshold of 55 cm was selected for practical reasons, as the user needs to be able to stand a minimum of 20 cm from the reader antenna in all positions, according to the reader manufacturer. Further, a success rate of 95% (means 95% of orders completed were rightly completed by the user and accepted by the software) was selected, as in a previous study focusing on hand gesture recognition,[25] the results returned a success rate of more than 96%.

The measurement results of the interface gloves with antennas from stretchable and non-stretchable electro-textiles are shown in Table 2 and Table 3, respectively. As can be seen, the gloves showed overall success rates of 94–98% and 93–100% in the home environment and the office environment, respectively. Thus, most of the results were successful, according to the threshold of 95%. The read ranges of the gloves, when measured with the M6 reader, were 40–80 cm and 65–110 cm, in the home environment and in the office environment, respectively. Thus, most of the results were successful according to the threshold of 55 cm. According to the results, there was no difference between the testers who were familiar with the systems and those who were not familiar with them. The read ranges in the office environment were longer than those in the home environment, most probably because of the multipath radio waves' reflection from metallic furniture, computers and other surroundings. The read ranges were also longer for the gloves that had non-stretchable electro-textile antennas, which is due to the lower resistivity of the conductive textile. Further, the read ranges were longer for the gloves that had embroidered antenna–IC interconnections, most probably due to the better and more reliable electrical connection. In a previous study, it was reported that embroidered antenna–IC connections are reliable, as the wireless performance of the tag remained the same after harsh stretching.[26] Further, glued antenna–IC interconnections also showed suitable reliability.[26] In the case of challenges, the reliability of antenna–IC interconnections can be increased, for example, with an epoxy coating.[27]

Table 4 presents the overall success rate of each finger separately for all the gloves. This is an average

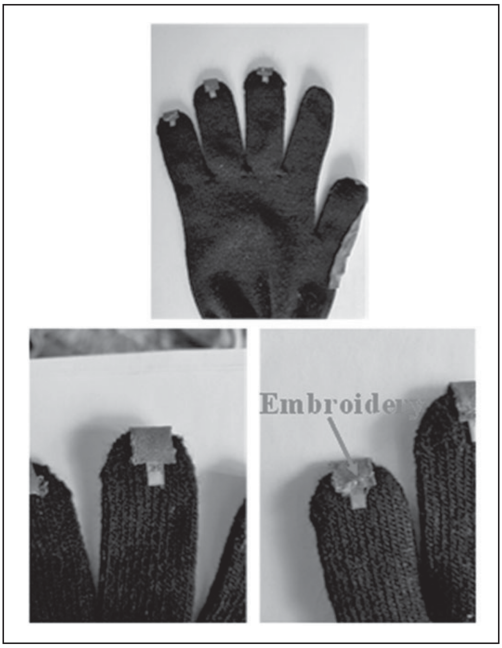

Figure 5. Interface glove from stretchable electro-textile: palm side of the glove (top), glued integrated circuit (IC) attachment (bottom left), and embroidered IC attachment (bottom right).

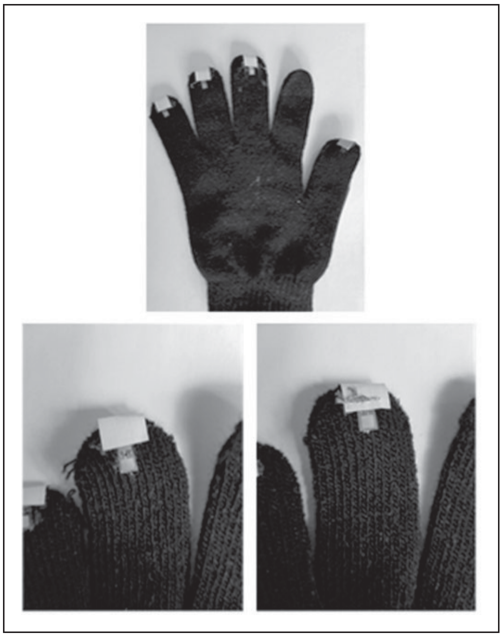

Figure 6. Interface glove from non-stretchable electro-textile: palm side of the glove (top), glued integrated circuit (IC) attachment (bottom left), and embroidered IC attachment (bottom right).

of the collected data from the four users in the office environment (which includes people who were familiar and people who were not familiar with the gloves). The presented data validate that the fingers (1–3) are all showing excellent success rates. Further, the gloves have no electronics or antennas inside. Thus, the gloves feel like normal gloves. When testing these first prototypes, the users had no problem while performing the given task. Initially, a detailed introduction and demonstration of the glove (how does it work) was given to the users. They straightforwardly used the glove for testing and had not really encountered any problems. Thus, the gloves are easy to use. We fabricated two pieces of each type of glove, and both gloves in each case showed similar performance. As Table 4 presents, the results for each finger of the gloves and the success rates were above 98%. Thus, we can conclude that the stability of the gloves is good.

These initial results indicate and provide important evidence for the further product development process of the next prototype: We are able to select the antenna material for the next prototype. Further, we know that the read ranges are longer for the gloves that have embroidered antenna–IC interconnections, and thus we can select embroidery (a very cost-effective fabrication method, as the conductive thread only costs about 1 euro per gram and is already a standard fabrication method used in cloth manufacturing) for the next prototypes.

The read ranges measured with the mobile handheld reader for all types of interface gloves are shown in Table 5. The maximum distance at which the reader can detect the input from the interface glove has been marked and measured on the floor. Three users tested these gloves and the measurement results were similar for all of them. As can be seen, the read ranges were between 35 and 80 cm, while longer read ranges were again measured in the office environment. These read ranges can be considered suitable for many practical applications.

Finally, as shown in Figure 9, a practical use situation evaluation of identification and access control was carried out. A mobile reader was fixed on an office door at 30 cm from the user. The door was given an access code of 231, which was given by the specific glove (only the identified person can access the reader, identification) in the right order (the right finger movements needed to be done, access control). The mobile reader identifies middle finger (digit 1), ring finger (digit 2) and little finger (digit 3) because each IC has a unique ID. The mobile reader application connects the ID to the digit and gathers the sequence of the

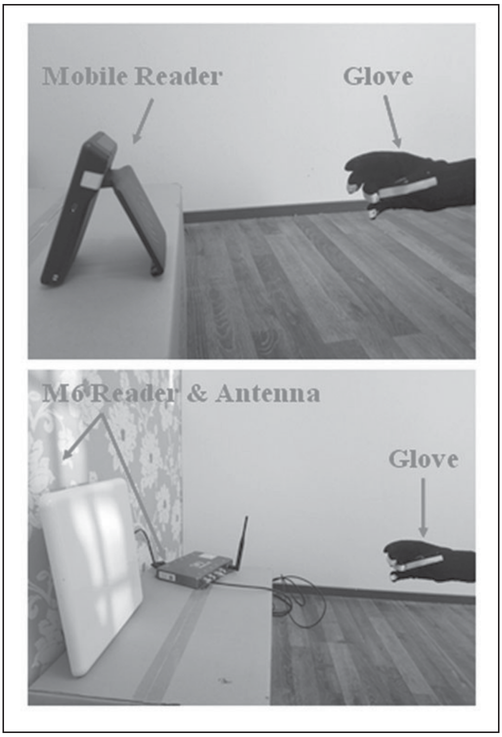

Figure 7. Test setups in a home environment: read range measurements with a mobile reader (top) and system evaluation with a M6 reader (bottom).

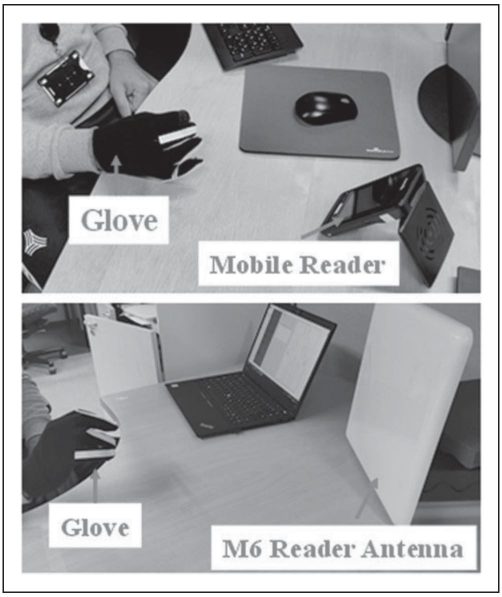

Figure 8. Test setups in an office environment: Read range measurements with a mobile reader (top) and system evaluation with a M6 reader (bottom).

digits. The mobile reader is connected to a background system through Wi-Fi and can thus be used for opening the door with the right sequence of IDs and resulting digits. Two people tested the door system successfully, which supports the idea of utilizing this glove for practical use with the mobile reader.

Future work

The next prototypes will be fabricated using embroidery with conductive thread as the IC attachment method. Further, we will be testing different antenna designs to improve the read ranges of the developed gloves. As the next step, we are integrating more ICs in different parts of the glove to enable versatile finger movements and hand gestures to be detected and classified as the desired inputs. In addition, statistical analysis on the difference in results, considering participants' familiarity with the technology and different user environments, will be part of the evaluation of the next glove interface prototype. In the future, our goal is to use the glove with a mobile phone-integrated UHF RFID reader, which will make the system fully mobile, as it will be both powered and controlled through the mobile phone. Further, the glove-integrated user interface will be able to take advantage of any auxiliary or external technology, which can be connected to the system through the mobile phone's Bluetooth or Wi-Fi connection.

These interface gloves have countless applications in several fields. This type of intelligent glove could be used to improve work efficiency and safety—for example, in replacing paper and pen by using hand gestures for writing simple notes, or by accessing doors by giving the right password with the identified person's work glove. Further, we imagine this glove to support people's independence by enabling simple control of ambient assisted-living applications, such as controlling lights and temperature or asking for help. Most importantly, we see communication possibilities for people with speech and language problems. This glove could, for example, be used as a sign language translator for deaf people, as well as to translate gestures into speech through a mobile phone for deafblind people. The healthcare sector has many applications which will become more fun and easier to handle with these gloves, for example, when considering playful physiotherapy exercises for children. With the help of our user interface and personally designed software, people could overcome communication participation restrictions related to physical limitations.

Table 2. Measurement results for gloves from stretchable electro-textile

User/Environment	Glued IC		Embroidered IC	
Familiar	Success rate (%)	Read range (cm)	Success rate (%)	Read range (cm)
Female 1/home	96	40	96	60
Male 1/home	94	40	96	60
Male 2/office	99	65	97	80
Female 2/office	99	65	96	80
Not familiar				
Male 3/office	98	65	97	80
Male 4/office	99	65	99	80

Table 3. Measurement results for gloves from non-stretchable electro-textile

User/Environment	Glued IC		Embroidered IC	
Familiar	Success rate (%)	Read range (cm)	Success rate (%)	Read range (cm)
Female 1/home	98	60	98	80
Male 1/home	97	60	98	80
Male 2/office	98	80	93	110
Female 2/office	97	80	96	110
Not familiar				
Male 3/office	99	80	99	110
Male 4/office	99	80	100	110

Table 4. Average success rates of fingers 1, 2 and 3 for all glove interfaces

Finger	Average success rate (%)
1	98.5
2	99.7
3	99.6

Table 5. Read ranges with handheld reader

Material/Environment	Glued IC Read range (cm)	Embroidered IC Read range (cm)
Stretchable/home	35	40
Stretchable/office	45	55
Non- stretchable/home	55	75
Non- stretchable/office	65	80

It should be noted that the final versions of these glove interfaces need to be washable, or at least they need to endure moisture. Previous studies about the washing reliability of these ICs and RFID tags fabricated from the same electro-textiles and conductive thread[28–30] have made it obvious that the electro-textile and embroidered antennas, as well as the RFID ICs, need a protective coating to shield them from moisture and mechanical stresses caused by a washing machine. For example, an epoxy coating has been found to be well suited for shielding the RFID tag ICs and antennas from moisture and detergent.[27] Thus, this will be tested with the next prototypes.

Figure 9. A user interacting with the mobile reader to access the door.

Conclusion

In this paper, we introduced a passive UHF RFID-based interface glove, using a cotton glove and tag antennas from two types of electro-textiles. Further, both conductive glue and embroidery with conductive thread were tested for antenna–IC interconnections. The developed glove interfaces were evaluated in a home environment and in an office environment by six test subjects. According to the results, the gloves showed high success rates (93–100%) for finger movement detection, as well as read ranges of 40–110 cm and 35–80 cm with an external RFID reader and handheld RFID reader, respectively. According to the results, there was no difference between the testers who were familiar with the systems and those who were not familiar with them. The read ranges in the office environment were longer than those in the home environment, as a result of the multipath radio waves' reflection from metallic furniture, computers and other surroundings. The read ranges were also longer for the gloves that had non-stretchable electro-textile antennas, which is due to the lower resistivity of the conductive textile. Further, the read ranges were longer for the gloves that had embroidered antenna–IC interconnections, most probably because of the better and more reliable electrical connection.

These first results are very encouraging, particularly when considering that the glove-integrated user interface, being a seamless part of the cloth and functional without an onboard power source, promises versatile applications for assistive technology in communication and in ambient assistant living. Further, it offers comfort and safety for versatile work environments. The fundamental strengths of the interface gloves implemented here remain within its passive nature and cost-effective, simple implementation into gloves. As the electro-textile materials can be easily integrated into different types of textiles, the fabrication of such interfaces can be carried out during normal glove manufacturing processes. Our goal is to make the system fully mobile, which requires a mobile RFID reader. The most convenient solution is to integrate the reader into a mobile phone, which can be kept 50–100 cm away from the user. Further, for people with different disabilities, when the mobile reader is attached to a bed or to a wheelchair, the user will be able to use this glove to communicate from a different room, different floor, or even a different building. We are next aiming to achieve longer read ranges ($\sim$1 m) and above 96% success rates for our next-version prototypes in all use environments.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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PUBLICATION VIII

Passive RFID-based Intelligent Gloves for Alternative and Assistive Communication–A Preliminary Study

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Passive RFID-based Intelligent Gloves for Alternative and Assistive Communication – A Preliminary Study

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***Abstract*—We introduce intelligent gloves based on passive ultrahigh frequency (UHF) radio frequency identification (RFID) technology, which comprises of four antenna parts and three RFID integrated circuits (ICs). Each of the ICs (in middle finger, ring finger and small finger) have their unique IDs, which can be activated by gentle touch of thumb, and used to send a specific message, which is displayed on a computer screen. Two users tested the gloves in an office environment with M6 mercury RFID reader and a specially developed software. The achieved success rate in these preliminary tests was 100 %. We consider these results promising first steps for future wearable passive RFID-based augmentative and alternative communication (AAC) solutions.**

Keywords— Alternative and assistive communication (AAC), passive radio frequency identification (RFID), special needs, wearable electronics.

I. Introduction

Recently, versatile body-centric intelligent devices have shown to provide human-computer interaction inputs based on body movements, gestures, and/or touch [1]-[6]. Especially passive ultrahigh frequency (UHF) radio frequency identification (RFID)-based wearable human-computer interaction has gained a lot of research interest lately [4]-[6].

When integrated into basic gloves, passive RFID technology enables tailored augmentative and alternative communication (AAC) solutions, which can solve the challenges related to currently available high-tech AAC solutions, such as touch-enabled systems or separate AAC devices, which are often restrictive for users who are physically or cognitively impaired [7].

In this study, we are presenting intelligent passive RFID-based gloves, where the IC activation works on the principle of on/off, and which comprises of four copper tape antenna parts and three RFID integrated circuits (ICs). Each of the ICs (in middle finger, ring finger and small finger) have their unique IDs, which can be activated by gentle touch of thumb, and used to send a specific message, which is displayed on a computer screen.

II. Intelligent Gloves

The first prototypes of these cotton-based intelligent gloves were presented in [8], where the detailed manufacturing process of the glove antennas from copper tape was presented. The findings were encouraging, as the gloves showed reliable on/off functions by finger movements in an office environment. This motivated us to present a real-life application, which is a simple wearable AAC solution.

The fabricated intelligent gloves are shown in Fig. 1. When the copper tape antenna on the thumb touches the IC pad on the finger antenna (also fabricated from copper tape), the specific IC on the finger is "turned on", which means it becomes readable for the RFID reader. Thus, only the touched IC is readable, while other ICs are "turned off".

Fig. 1. Integrated copper tape antennas on the palm side of an intelligent glove (left) and on the backside of an intelligent glove (right).

In our system, each finger corresponds to a special message, which appears in an image format on a computer screen. The fingers 1) middle finger, 2) ring finger and 3) small finger correspond to 1) "I have something to say", 2) "I need assistance" and 3) "I need urgent assistance" messages, respectively. These messages (shown in Fig. 2) are important alert messages for people who are unable to speak and need assistance in communication and activities of daily living.

Fig. 2. Messages corresponding to respective ICs in middle finger (top left), ring finger (bottom left), and small finger (right).

III. Testing and Measurements

The intelligent gloves are tested in an office environment (see Fig. 3) with people, computers and cell phones around, making it an ideal environment for practical testing. The testing setup includes a M6 RFID reader, which operates at the European UHF range (865.6-867.6 MHz) and with a power of 27 dBm. The M6 reader is connected to a circularly polarized RFID reader antenna through a connecting cable.

The testing setup includes a specially developed software, a WinForms desktop application, which uses ThingMagic library to connect and communicate with the M6 reader. The reader detects the IC and triggers an input with the specific ID of the IC through the "TagRead" function. In this preliminary test, the detected input of a specific ID returns output in a picture format on the computer screen.

Fig. 3. Testing setup of AAC gloves in an office enviroment.

In the test, two users, both familiar with the used passive UHF RFID technology, are given 200 random orders, the user acts correspondingly, and the output is shown on the computer screen as a picture with a specific message. A wrong picture or no picture is considered a failure. As shown in Table 1, both users achieve a 100 % success rate in this preliminary test. Thus, we can consider these prototype gloves as promising first steps for future wearable passive RFID-based AAC solutions.

TABLE I. Success rate of measurements taken in an Office environment

User	Success rate
User 1	100 %
User 2	100 %

IV. Discussion

The main advantage of the "AAC glove" presented in this study, is its passive nature: There is no need for a battery in the glove. Further, it is possible to tailor the amount of RFID ICs in the glove, which means we can use different types of hand gestures as inputs to the world around us. We will further explore the possibilities of these gloves by bringing new outputs in the forms of pictures, texts, and sounds. As the output can be tailored for each individual user and use environment, the developed system provides great flexibility for practical use. In addition, it's essential that AAC solutions are easily available and fast to use in everyday life.

V. Conclusion

A basic cotton-based glove with integrated passive UHF RFID technology provides the possibility of giving inputs to the surrounding world through a specially developed software and a basic M6 RFID reader. The developed intelligent glove has three input points in fingers (in middle finger, ring ringer and small finger) and each corresponds to a message ("I have something to say", "I need assistance" and "I need urgent assistance", respectively), which is shown on a computer screen.

In this preliminary study, the developed glove was tested by two users with a 100 % success rate. Based on the achieved results, these intelligent gloves provide new possibilities for easily available and individually tailored AAC solutions. The possibilities of the gloves in teaching and learning, as well as in the entertainment sector, for example as game controllers, are interesting future aspects to study as well.

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