Pervasive Assistive Technology for the Deafblind

Need, Emergency and Assistance through the Sense of Touch

Nicholas Caporusso, Michelantonio Trizio, Giovanni Perrone

Abstract Deafblind people have some degree of combined impairments of both the visual and the auditory channels. In the scenario of sensory disabilities, deafblindness is among the worst cases. Fortunately, it only affects a small percentage of the population. Being a niche market, in turn, is one of the main reasons why spending in innovation is not considered profitable both by companies and by investors. Indeed, deafblindness is a rare, challenging, demanding, and urgent situation. Although dealing with this type of disability can be complex, the needs of deafblind people are the very same as that of the sighted: independence, access to information, social integration.

The objective of this work is to review currently available assistive technology that is suitable for helping the deafblind in their daily life. Specifically, we focus on systems that support basic functional communication in case of need, emergency, and assistance. ADD MEANING HERE

1 Introduction

According to demographic studies by the World Health Organization (WHO), the world's blind population is about 37 millions. Other studies estimate that the numbers are between 40 to 45 millions. This figure adds to 123 million people suffering from ipovision or vision impairments (i.e., the ratio between the blind and individuals affected by ipovision is 1:3.4), and 314 million have some kind of major visual impairment. In industrialized countries, approximately 0.4% of the population is

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blind, whereas 90 percent of the blind live in developing countries (i.e., 27% S.E. Asia, 26% W. Pacific, 17% Africa, 10% E Mediterranean, 10%Americas, and 10% Europe), where limited access to resources and technology aggravate the problem.

Less is known about the deafblind: statistics are unavailable in many countries. This is because there is no common opinion about what deafblindness is, and to what extent people are considered deafblind. Moreover, due to their particular condition, many deafblind individuals are difficult to categorize in censuses. Therefore, numbers are estimated, only. According to recent statistics, there are roughly 50000 deafblind people in the United States, which represent roughly 0.016% of the population. It can be calculated that there are about 150 million deafblind individuals, by taking into consideration the demographics of industrialized countries.

Although deafblind people represent a significantly small minority of the world population, they are an important challenge in terms of public health and policies. School and working-age blind have very high unemployment rates (about 75%, in the most accessible countries). Moreover, only 10% of blind children receive instruction in Braille. Not only is this a matter of social security, as it involves the ability of the deafblind population to achieve autonomous living, independent mobility, and social inclusion.

As such individuals are deaf and blind at the same time, they are not able to rely on their sight or on their sense of hearing to communicate with others and to interact with the external world. As a result, they are forced to utilize an alternative channel for achieving communication, interaction and access to information.

The purpose of Assistive Technology is providing individuals suffering from many types of different disabilities (e.g., from cognitive problems to physical impairment) with support to individual tasks. Designing an assistive interface implies investigating the relationship between the willingness of using some technology and a temporary or permanent inevitable condition that renders technology compulsory or adds urgency to the need of technological aids. That is, in a scenario of fashion high-tech gadgets, for some people digital devices are not an option. This is the fundamental principle by which interaction designers have the objective of providing people with real support to their basic and fundamental needs.

Nowadays, adaptive technology has a substantial impact on people with sensory, cognitive, and developmental impairments. Also, it has significant benefits for the deafblind: it allows them to achieve communication and to overcome obstacles that seemed overwhelming ten or fifteen years ago. As a consequence of the introduction and the use of technology to close the digital divide with people with disabilities, the deafblind will benefit from more options for education, training, and future employment. Regardless of the complexity and of technology advancement, still individuals will require better systems to be autonomous in communication, to and independently move and interact with the environment, and to get unrestricted access to information. Most importantly, proper technology and training can help them decrease the feelings of isolation, and achieve a complete and fun social life.

In case of impairments to one sensory channel, *sensory substitution* is a technique that can be utilized to replace the missing (or less performing) sense with another. As an example, blind people use the sense of hearing as a replacement for vision. Among the residual channels, the sense of touch is the best sensory substitute: although it is less performing than vision and hearing, it enables exchanging messages with the environment. Nevertheless, in order to be accessed for exchanging messages (communication) or for acquiring information, people and objects have to be at contact distance. This major drawback can be mitigated by introducing assistive technology (AT) in the form of novel human-computer interfaces that enable individuals to go beyond close proximity and to interact with a world that is, day after day, one step forward.

In this regard, tactile and haptic interfaces have great potential in rendering the environment accessible to the blind. Particularly, they address specific shortcomings of traditional sensory substitution approaches based on auditory output and, thus, they are especially suitable for the deafblind. However, they have particular requirements in terms of design. In this chapter, we focus on the several different aspects involved in the design, development and adoption of novel tactile interfaces for the deafblind.

In this work, we review the main assistive technology currently available to blind and specifically deafblind people.

2 Glossary

With respect to directionality of messages, we intend communication processes as based on the concept of messages being passed from sender(s) to receiver(s). In this dissertation, we apply a user-centric approach and, thus, we will use the following conventions:

- *input system* (*input*) refers to a machine agent capable of receiving messages sent by the human agent, or to the situaton in which the human agent sends messages;
- *output system* (*output*) refers to a machine agent capable of sending messages to the human agent, or to the situaton in which the human agent receives messages;
- *input/output system* (*input/output*) intuitively refers to a machine agent capable of receiving messages from and sending messages to the human agent.

Where not explictly stated, the words *system*, *device* e *peripheral* e *solution* are utilized to refer to the object per se, and they are employed as synonyms, as they do not refer to any specific architecure, operating mode, or communication protocols.

Moreover, when we refer to touch-based communication, our approach is extremely strict: although tactile communication can be associated with spoken language (as in the case of blind people) or visually-perceivable gestures (e.g., in sign languages employed bu the deaf), we only focus on the tactile component of interaction (or communication), and we take less into consideration the visual or auditory elements.

In this dissertation, we will use the terms "*touch-based communication*" in reference to the tactile component of messages, only, even if several communication systems simultaneously use two perceptual channels in order to exchange information. For instance, the sign language utilized by the deaf combines tactile and visual communication; also, blind people utilize tactile displays in combination with auditory output. However, as this work focuses on people with a combined degree of visual and auditory impairments, we will only take into consideration touch.

3 State-of-the-art

Although the world is perceived as mainly structured into visual and auditory stimuli, the sense of touch plays a fundamental role in human perception, as it enables individuals to communicate with others and acquire a variety of pieces of information about both the environment and the external world. Touch is the first sense being formed in humans: sensitivity to tactile stimulation is already developed at the eighth week of gestation of an embryo [**?**]. Also, it is among the senses that still are available when sight and hearing start to fade.
Despite its simplicity and its longevity, the sense of touch is not to be conceived as *primitive* with respect to vision and audition. In addition to being an informative and perceptual system of sensing, it includes features that enable bidirectional exchange of information and active communication [**?**]. Nevertheless, vision and hearing are the major senses through which individuals perceive the world and communicate with others, because they utilize the most convenient perceptual channels in terms of information throughput. As the majority of humans mainly rely on the visual and on the auditory channels to perceive the world, also verbal and nonverbal communication methods usually utilize the sight or the sense of hearing as primary channels for exchanging messages [**?**]. As a consequence, despite its potential, touch is fundamentally utilized for simply acquiring information about the environment in close proximity, and for manipulating objects in everyday tasks. Eventually, touch-based communication systems receive less attention. Regardless of the communication system, the majority of purely tactile languages are not utilized by the deaf, who prefer to utilize their vision (or residual vision) to interact with the environment, with computers and with others. Conversely, thanks to the introduction of digital tools for supporting a variety of tasks (e.g., reading books), the blind increasingly utilize auditory feedback instead of traditional touch-based communication systems dedicated to the visually-impaired, such as the Braille alphabet.

Several touch-based systems are available for informative and communication purposes. Specifically, tactile languages allow exchanging messages between individuals, and they are particularly suitable for enriching or complementing verbal communication in situations of impaired sight, if the sense of hearing is affected by some impairment. In general, communication systems based only on touch are utilized when the auditory or the visual channel are affected by noise, such that the reception of the message is compromised to some extent. Furthermore, people who are affected by multiple sensory impairments to the visual and the auditory channels (i.e., the deafblind) have the only choice of using touch for accessing the external world both for communication and for information retrieval purposes.

Assistive technology and specifically, pervasive health technology [**?**] has great potential in improving the quality of life of people with physical and sensory disabilities. Also, it plays a crucial role in supporting their education and their social inclusion. Although research produced advances in technology that supports blind and deaf users, in the last decades less attention has been dedicated to people that are not able to rely on both the visual and the auditory channels. Also, there are several publications that review the main technology advancements devoted to people suffering from physical, sensory or cognitive impairments. However, there is poor literature about assistive and communication devices especially designed for the blind and, particularly, for the deaf-blind. Nevertheless, research addressed multisensory impairments as a hot topic in the last years. For instance, a paper published in 1986 [79] introduced a system based on Braille displays that could help the deaf-blind to receive messages from a computer. More than 25 years later, and despite the evolution of technology, the deaf-blind still have poor alternatives. The lack of technology for helping multisensory impaired people is the starting point for our research. To this end, in this chapter, we review the most relevant devices for people with sensory impairments. In our study, we take into consideration research projects discussed in papers published in international journals or presented at conferences, technology under development, and commercial products that already are on the market. In particular, our interest will focus on innovative Human-Computer Interfaces based on touch, which are the only suitable for the deaf-blind. For convenience, we distinguish assistive technology into the following three broad categories:

- augmented functional communication tools
- language-based devices
- systems for environment interaction.

3.1 Aids for functional and augmented communication

Augmentative and Alternative Communication (AAC) devices include all forms of communication aids that can be utilized to express thoughts, needs, desires, and ideas. In general, all individuals use AAC in their facial expressions or gestures;

also, symbols, pictures, or writings incorporate features and pieces of Augmentative and Alternative Communication. People with severe disability or physical impairments rely on AAC as a supplement or replacement of sophisticated communication, especially if their goal is to simply communicate their needs and reach the final objective of being understood by the receiver of their message. Special Augmentative and Alternative Communication, such as picture and symbol communication, use aids (e.g., boards and electronic devices, picture cards, and all available objects that are meaningful) to help people express themselves. Moreover, Augmentative and Alternative Communication helps people with poor literacy or limited communication increase the performance of their social interaction, and enable them to achieve basic education. The devices described in this section fall in the category of technology for functional and augmented communication due to their limited complexity that, simultaneously, grants them effectiveness and low entry barriers.

3.1.1 ComTouch

ComTouch [35] augments remote voice communication with the use of touch. In order to do so, it converts hand pressure into vibrational intensity, so that users can feel each others' touch cues in real-time, despite being remotely located. ComTouch consists in a handheld device: it incorporates a vibrotactile-actuator-enabled sleeve that fits over the back of a mobile phone. The device supports bi-directional communication, so that wo users can simultaneously send and receive vibrotactile cues. ComTouch can be utilized to enable basic communication between the deafblind and their relatives. In addition to vibrotactile actuators, the device incorporates speakers, so that the device can be utilized by blind people as well. Fig. **??** shows the touch-to-vibration mapping. The component responsible for the input is located on the fingertips. This is where flexor muscles allow ufficient dynamic physical range to control a downward pressure. A voltage controlled oscillator (VCO), converts signals acquired through the input component into oscillation, and the result is transmitted to both the speakers and vibrotactile actuators. The VCO output is designed such that it generates a maximum pressure corresponding to a maximum frequency of 250Hz.The output feature exploit vibrations that that are fired on the middle phalanx and on the proximal phalanx of the finger, as this area provides the largest contact surface on the hand. Specifically, pressure-sensitive force-sensing resistors incorporated in the input subsystem have the role of measuring pressure. They have enough sensitivity to discriminate pressure ranging from approximately 0.45 Pounds per Square Inch (psi), i.e., soft touch, to 150 psi, that is, squeeze. Fig. **??** show a prototype of the system. Colored areas help sighted users to understand the touch-to-vibration mapping. The device allows users to communicate with one finger, and using the pre-defined touch-to-vibration mapping, only. This is realized by placing the left hand on the upper surface of the device so that the tip of the index finger corresponds to the yellow pad. Pressing the yellow button causes a vibration in the middle phalanx (i.e., located on the green pad). This vibration is the local feedback signal, and it allows the user to modulate their signal both in amplitude and in frequency. Simultaneously, users input is sent to the other pad, where it is received in correspondence of the proximal phalanx (i.e., firing the blue pad). ComTouch provides each user with control over their output thanks to local feedback that help them modulate the intensity of the signal to be transmitted. The preliminary implementation [35] allows two people to communicate through vibrotactile stimuli using their index fingers, only. Unfortunately, this device is not on the market, to our knowledge.

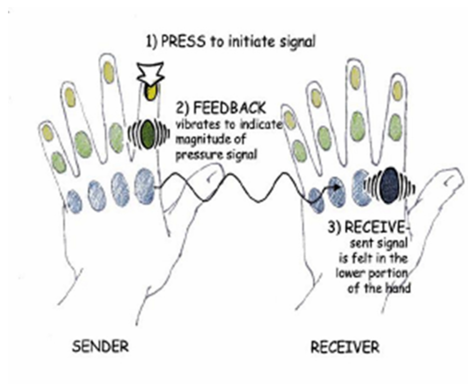

Fig. 1: Touch-to-vibration mapping in ComTouch

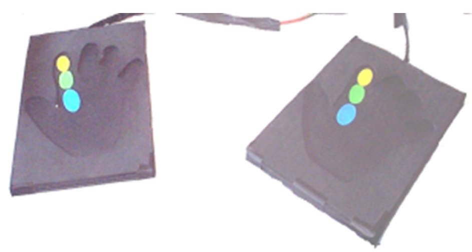

Fig. 2: Preliminary implementation of ComTouch. Vibrotactile communication over one finger is transmitted between two pads, in a bi-directional fashion.

3.1.2 Tactor suit

Bloomfield et al. [36] employed smart textiles in the design of a method for providing blind and deafblind people with localized vibrotactile cues. The Tactor suit incorporates vibrotactile actuators (tactors) into a standard sweater. The location of tactors is associated to a human model so that the system can trigger real-time localized feedback on the torso. The objective of the system is to train blind and deafblind people in moving into simulated environments, so that they can learn the position of obstacles by receiving vibrations when they collide with an object. They hypothesize that vibrotactile feedback can be effectively employed in improving users' mobility. Moreover, the tactor suit is designed to provide physical realism in regard to interaction with objects and with the environment. Experimental results show that the vibrotactile suit is able to improve users' performance in navigating virtual environments. However, the system is not suitable for supporting users in their actual mobility.

Fig. 3: Tactor suit

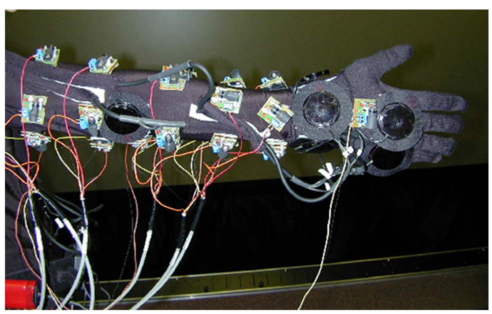

Fig. 4: Tactor suit with the tactors attached

3.1.3 Hey yaa

Hey yaa [37] is a wearable system based on haptics that supports functional communication using vibrotactile cues. The purpose of the device is to deliver touch stimuli and to signal events and to provide users with alarms. Hey yaa is based on Arduino Lilypad, and it consists of two waist belts. Similarly to Comtouch, two devices communicate with one another. When one belt is pressed, the other one vibrates, drawing user's attention. In contrast to ComTouch, Hey yaa is wearable and thus, it can be utilized in everyday tasks to keep constant contact with an assistant.

Fig. 5: Hey yaa belt in two different ways: hiding or showing the electronic components.

3.1.4 the Hug Shirt and Hug Me

Similarly to the Tactor suit, the Hug Shirt [38] enables delivering touch cues on the torso. Specifically, the purpose of the device is to transmit hugs. Although it might seem trivial, it is crucial for the deafblind to receive comfort through physical contact. The device incorporates sensors capable of acquiring the strength of the touch, the warmth of the skin and the heartbeat rate of the sender. Also, the Hug Shirt includes actuators that reproduce the touch sensation of a hug, including warmth, so that the recipient can receive semi-realistic sensations. The system consists of a shirt equipped with sensors and actuators and a smartphone application that communicates via Bluetooth with the shirt. The application enables the sender to design virtual hugs (i.e., without actually wearing the shirt) to be transmitted to the receiver, and vice versa. HugMe [39] adds auditory and visual information to touch interaction. Despite its applications in the medical field (e.g., for children and the elderly [40]), it is not suitable for the deafblind.

3.2 Language-based devices

The number of communication methods has grown significantly over the past two decades: from email to instant messaging, from text messaging to voice over IP, or video conferencing. Technology advancement both in hardware and software, allowed developing sensors and actuators are being developed to enable more complex messages to be communicated through haptics, which uses the sense of touch. It is one of the oldest forms of communication. Haptic communication overcomes communication barriers for blind and deaf people but also for deaf-blind people too or where dangerous, dark, or noisy environments prevent the effective use of auditory or visual communication methods. Even for this subsection are presented and described a set of devices pertaining to such category.

3.2.1 Braille displays

Currently, all refreshable Braille displays [41] consist of Braille cells that incorporate 6-8 dots arranged in a 2x3 or 2x4 matrix. Braille cells use piezoelectric ceramic bimorph reeds to raise or lower Braille dots by approximately 0.5mm above the reading surface. ADD MORE HERE.

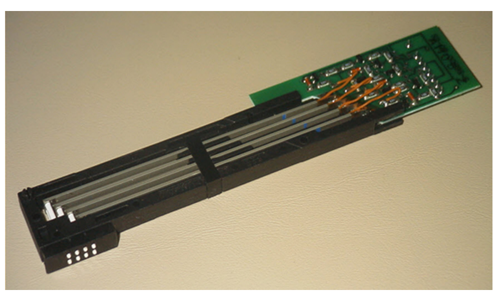

Fig. 6: Typical Piezo Braille Cell

Fig. 7: Model of 20 Cell Braille PDA

3.2.2 b2g

Developed by National Braille Technology [42], Braille to Go (B2G) is a Braille-based mobile computing device. It incorporates a refreshable braille display specifically designed for blind and deafblind people. Basically, Braille to Go is a standard Android smartphone with a Braille display in place of a standard visual display. It consists of an array of cells that work as an output syste, Also, it includes a Braille keyboard. The B2G is small and portable (its size is about half that of a sheet of paper).

3.2.3 VBraille

V-Braille [43] is a way to represent Braille characters in a haptic form on a standard mobile phone, using the touch-screen and vibration. V-Braille may be suitable for deaf-blind people who rely primarily on their tactile sense. V-Braille is a simple mechanism for conveying Braille using the touchscreen and vibration on a mainstream phone. The software was developed for the G1 under the Android platform. The screen is divided into six parts, to mimic the six dots in a single Braille cell (see Figure).

When the part of the screen touched (any point within the enclosing 1/6th region) represents a raised dot, the phone vibrates. Touching dot areas 2 and 5 present stronger vibrations (shown by the solid line in Figure 2.8), making it easier for users to differentiate between vertically adjacent raised dot areas. The screen can be tapped or stroked in different sections and directions. Grade 1 Braille is used for testing. The average time it took for a participant to read a V-Braille character ranged between 4.2 and 26.6 seconds. Five out of nine users were able to read a character in less than 10 seconds. Together, their nine users had a 90

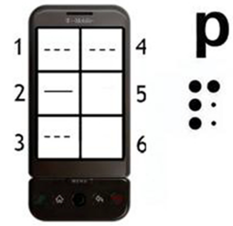

Fig. 8: V-Braille representation of the lowercase letter p on a smartphone touchscreen, simulating localized vibration on Dots 1 through 4. Dots 2 would vibrate more strongly in this case, as would 5 if it was raised.

3.2.4 Mobile Lorm Glove

The Lorm Glove [45] is a mobile communication and translation device for the deaf-blind that translates the hand-touch alphabet Lorm (a common form of communication used by people with both hearing and sight impairment) into text and vice versa. This device enables the deaf-blind user to compose messages via fabric pressure sensors placed on the palm of the glove to be transmitted as an SMS to the receivers handheld. Initiated by small vibrating motors located on the back of the glove, tactile feedback patterns allow the wearer to perceive incoming messages. This device is based on Lorm alphabet, developed in the 19th century by deaf-blind inventor Hieronymus Lorm. It is a tactile handtouch alphabet, in which every character is assigned to a certain area of the hand (see Figure 2.9). The speaker touches the palm of the reader's hand to sequently draw the characters onto it by tracing lines and shapes.

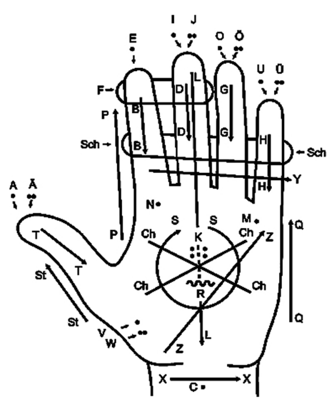

Fig. 9: The German Lorm Alphabet

People with deaf-blindness acquired late in life have the opportunity to use Lorm for communication with the outside world. This requires both interlocutors to be familiar with Lorm. Physical contact is indispensable. Those preconditions often lead the deaf-blind into social isolation and dependence on information relayed by people around them. The Mobile Lorm Glove is a hand glove made of stretchy fabric equipped with an input unit on the palm of the glove (see Figure 2.10) and an output unit on the back of the glove (see Figure 2.11).

Fig. 10: Input unit on the palm of the glove

Fig. 11: Output unit and control unit

The input unit consists of a matrix of 35 fabric pressure sensors similarly as described in [44]. 34 of the round shaped pressure sensors, which are 10mm in diameter, correlate with the different characters of the Lorm alphabet. The rectangular sensor located on the wrist of the glove is needed to signal the completion of an entered character. This sensor does not only differ in its shape and size, but also in its texture to clearly distinguish it from the other pressure sensors. The sensors are made from piezoresistive fabric, which changes its electrical resistance under mechanical pressure. The pressure sensors and the glove are stretchy so they can fit tightly to ensure maximal operating comfort. The predetermined pressure points can easily be traced along an embroidered tactile guidance system depicting the patterns of the Lorm alphabet. The output unit is defined by a matrix of 32 shaftless coin vibrating motors each with a diameter of 8mm, an operating frequency range of 200Hz and an operating voltage range of 3.3V designed for haptic vibrating feedback functions in handheld applications. Their location is again based on the patterns of the Lorm alphabet. They serve as direct feedback for the input sensors and translate incoming text messages into Lorm patterns. The sensor matrix of the input unit and the actuators of the output unit are connected to the control unit via flexible wires. The control unit and the power source are integrated in a case with an adjustable Velcro strip to be mounted on the forearm (see Figure 4). Two rocker switches on the case are used to turn the device on or off and to switch between input and output. The controller is designed of four 8-bit shift registers and four darlington transistor arrays controlling the 32 vibrating motors with an ATmega328 microcontroller. To implement the control of the motor intensity, pulse-width modulation (PWM) is used. The sensor data is transmitted to the microcontroller using a matrix design of two 8-channel analog multiplexer/demultiplexer. A Bluetooth module mounted on the controller board manages the data transmission between the Mobile Lorm Glove and the handheld of the user. The deaf-blind user wears the Mobile Lorm Glove on the left hand and uses the tips of the fingers of the right hand to Lorm onto his or her own left hand to compose text messages. The left hand is open with its fingers slightly spread. Once the wearer of the Mobile Lorm Glove receives a text message, it is forwarded to the glove from his or her handheld device via Bluetooth and translated into the Lorm alphabet. Initiated by the small vibrating motors, tactile feedback patterns allow the wearer to perceive the incoming messages.

3.2.5 Touch Communication Glove with Tactile Feedback

SSC Pacific has developed a glove [46] that can send and receive messages simply by moving fingers. Each finger is fitted with a sensor to measure movement, called an accelerometer, and a vibration motor which creates sense of touch feedback. Movements are translated into language and sent wirelessly from one glove to another glove in the form of vibrations that the receiving party feels. For example, if one user were to hold up the universal peace sign, the other user may feel the Braille writing for the word peace on his or her fingertips, and a computer monitor would display the word peace. In addition to person-to-person communication, this glove can be used to interact with computers, the World Wide Web, and even autonomous robotic vehicles. Entire books, e.g., could be communicated electronically to the blind using the glove.

This device is based on a communication language called Finger Braille, in which the index finger, middle finger and ring finger of both hands function like the keys of a Braille typewriter. In the original implementation, a sender dots Braille code on the fingers of a receiver as if typing on a Braille typewriter. The receiver is assumed to be able to recognize the Braille code.

Fig. 12: Glove prototype features motion sensors and vibration motors on each finger

3.2.6 Sign Language embedded in an Intelligent Space

We conclude this sub-section talking about this researchers who have designed a system which is able to recognize the signs using a video camera system: the recognized signs are reconstructed by the 3D visualization system [47]. To accomplish this task a standard personal computer, a video camera and a special software system was used. The software is able to recognize letters from the sign language alphabet with the help of color marks. The sign language recognition is a function of an Intelligent Space, which has ubiquitous sensory intelligence including various sensors, such as cameras, microphones, haptic devices (for physical contact) and actuators with ubiquitous computing background. To recognize all of the letters two or more cameras and a rather complicated marking system is needed so they limited their systems facilities to recognize those letters which neglect the use of thumb (some examples below):

For finding the joints of the fingers on the picture of the camera, they had to sign them: first they mark the joints with red points but two problems appeared: which point belongs to which finger and this point an inner point or an outer point. To solve this problem, different colors have to be used as it shown in the following figures, but in that case the finding of the joints would be more difficult, because there are more colors:

Moreover they used a system which uses a CCD video camera to recognize the finger positions:

To help their system, they used specially marked gloves as just described. The image of the observed hand is transferred to a standard desktop computer - using a video digitalizator card - where an image is analyzed by their image recognition program. If the analyzed hand is recognized as a sign for deaf people, the corresponding letter is displayed on the screen. While displaying a recognized letter the program is able to display the signs using a 3D hand visualization software. Finally,

Fig. 13: Camera picture of letter A

Fig. 14: Camera picture of letter B

multiple hand visualization programs can be connected to the recognition software through the Internet.

3.3 Systems for environment interaction

We conclude our review on assistive technologies considering three different categories of devices that allow individuals to interact with the environment in which they are embedded. In particular we are going to analyze devices for the mobility support, those that allow interactions with everyday objects and finally the indica-

Fig. 15: The inner color points of the prepared glove

Fig. 16: The outer color points of the prepared glove

tors and other signaling or warning devices in general. For each of these categories will analyze different devices that serve such purposes.

3.3.1 Devices for supporting mobility

We start considering Orientation devices that fall into the broader category of Electronic Travel Aids (ETAs). This class of systems helps people with disability overcome one of the most challenging limitations in their lives: achieve independent and autonomous mobility. Many systems for providing the blind with safe and independent mobility have been proposed over the last decades. The orientation devices have the purpose of informing the users of their current location and they assist them

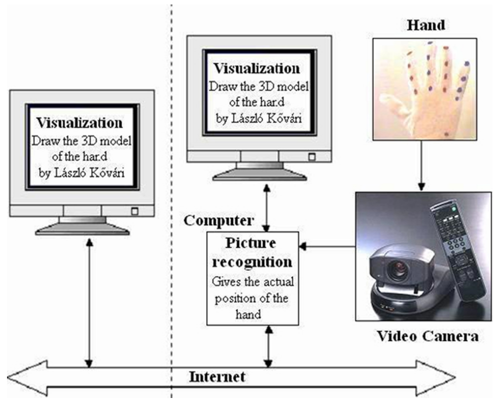

Fig. 17: The system for transfer information

on their journey by helping them find the direction in which they have to go to reach their destination. This, in turn, is based on the same operation principle, regardless of the technology being utilized: acquire spatial information from the environment and analyze it (e.g., process orientation), to signal objects or realize obstacle avoidance by means of algorithms. Such systems range from simple compasses to complex navigation systems. A number of devices to support the mobility of deaf-blind people also require modifying the environment (e.g., embedding wires in pavements, or adding transmitters at salient points). As a consequence, their adoption require complex decision-making processes at a municipality level. In the recent years, considerable resources have been devoted to developing navigation and wayfinding systems. Although compasses are the easiest type of orientation systems, electronic devices come into audible versions only. Indeed, there are low-tech tactile versions of compasses that use Braille. A research paper published by Langtao [48] introduced an electronic compass for the deaf-blind based on output in the form of electric pulses. Also, Nagel et al [49] designed a compass based on a vibrotactile belt based on a set of vibrators one of which (the one pointing north). Nonetheless, nowadays there is still no tactile equivalent of speech-based compasses. Devices such as the Miniguide [50], the Ultra Cane [51] and the hand-held ultrasonic obstacle detector developed by [52], indicate the distance to the closest object by vibrating when an obstacle is detected within a range from one to ten meters. The vibration frequency is an indicator of the distance of the obstacle: the faster the vibration rate, the closer the object. They are based on ultrasonic, laser or infrared technology, and they can be utilized by individuals to scan the environment and to build up a spatial map of their surroundings. The Step-Hear [53] and the infrared remote signage developed by [54], are information and navigation reference point systems. In general, such systems consist of two units: Base and Activator. The Base is installed in key locations, with pre-recorded information. The Activator is held by the user, and vibrates to provide proximity and directionality to the location. For instance, Van Erp et al [55] use a belt to indicate the direction towards the destination. Also, landmark navigation systems have been implemented with low-cost technology for indoor localization [56]. Regardless of the underlying technology for exchanging messages between the base and the activator, these systems require an infrastructure to be deployed in the environment. Even if this is a simple landmark transmitter, installing and maintaining permanent transmitter is extremely expensive and it does not help individuals navigating in areas that are not covered by the system. Portable orientation systems based on the Global Positioning System (GPS) are available to the deaf-blind population as extensions and add-ons to notetakers (e.g., the Braille Note, Braille Sense and the Pac Mate). Recently, they also come in the form of smartphone applications connected to Braille displays [57]. Studies about haptic forms of output for assisting GPS navigation are discussed in [58]. Unfortunately, nowadays there is no GPS system especially designed for the deaf-blind. Regardless of their output channel (i.e., Braille-based tactile output or speech-based auditory output), portable orientation systems allow the deaf-blind population to access basic information about current position, and to find routes toward destinations. For instance, they can help understand the route of means of public trasportation (e.g., bus) and to identify where they are stopping. Although GPS technology provides the deaf-blind who are able to travel useful information, these systems miss environmental information, such a whether there are sidewalks along the route. Indeed, GPS systems for the deaf-blind have the same reliability factor of mainstream GPS, and they suffer from poor reliability within a few feet or meters of an actual physical location. As an example, it is not uncommon for deaf-blind individuals to find themselves in the middle of a street instead of at the door to their favourite restaurant. The implications of such scenario are significant. Therefore, GPS does not offer a true replacement for orientation or mobility skills. Moreover, it does not replace any of the tools deaf-blind travellers already use (e.g., cane or service dog). Finally, they do not offer (or support notekeeping) any contextual information that can add to the experience of travelling, such as a description of the surrounding environment. Cardin and al. [59] presented an interesting system of obstacle detection for visually impaired people based on vibro displays. While moving in real world the user is alerted to close obstacles by using a multi-sonar system and appropriate vibrotactile feedback. The system proved to be effective in conveying spatial proximity and increasing the mobility of visually impaired people by offering new sensing abilities. We conclude this subsection by presenting and describing in more detail two further studies.

3.3.2 ActiveBelt

ActiveBelt [60] is a wearable interface that enables users to obtain multiple directional information with the tactile sense. Since the information provided by the tactile sense is relatively unobtrusive, it is suited for daily use in mobile environments. Moreover, it is a belt-type wearable tactile display that can transmit directional information.

ActiveBelt can enable users to intuitively obtain directional information in the real world simply by activating vibrators. Since a user can easily match this tactile

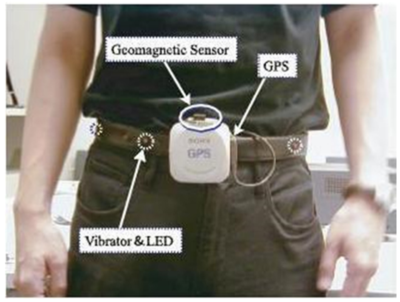

Fig. 18: Hardware of ActiveBelt ver.1

information to directions in the real world, the ActiveBelt can transmit effective information via the tactile sense. Also, this device doesnt require the user to wear or carry yet another device, since it attaches vibrators in a typical belt worn by many people in daily life. In addition, since people usually wear belts outside, ActiveBelt is well suited to use in mobile environments. So the ActiveBelt can be used for a variety of applications and especially for location-aware information services like navigation systems. The ActiveBelt consists of two sensors (a direction sensor and a GPS) to detect a users location and orientation, multiple vibrators to transmit tactile information, and a microcomputer to control these devices (Fig. 2.19). The vibrators are attached throughout a belt at regular intervals.

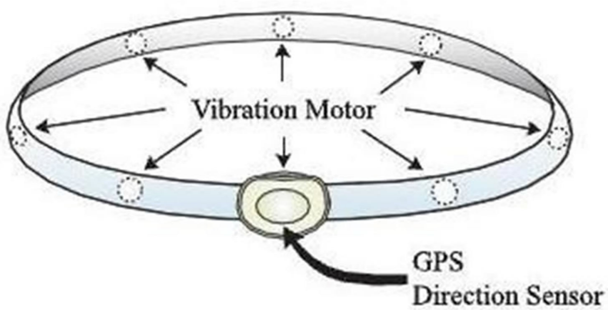

Fig. 19: Basic Concept of ActiveBelt

The prototype system consists of four components: (1) ActiveBelt hardware, (2) a GPS, (3) a directional sensor, and (4) a microcomputer (Fig. 2.20). Fig. 2.21 shows the system architecture of the ActiveBelt. Next, we explain each component of the prototype system.

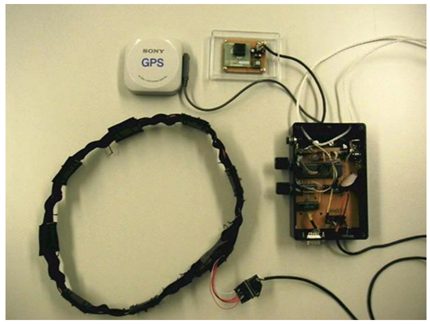

Fig. 20: Prototype system of ActiveBelt (1. ActiveBelt hardware, 2. GPS, 3. directional sensor, 4. microcomputer)

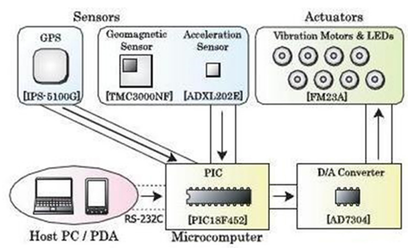

Fig. 21: System architecture of ActiveBelt

3.3.3 Finger-Braille interfaces for navigation of Deaf-Blind

The authors have implemented a Finger-Braille [61] interfaces for navigation of Deaf-Blind people and the ubiquitous environment for barrier-free application (Finger-Braille is one of the commonly used communication methods among Deaf-Blind people in Japan). In this work are developed two types of ring-shaped devices: (1) vibration motor type and (2) solenoid type (Figure 2.22).

(1) Vibration Motor Type (2) Solenoid Type

Vibration motor type consists of six small-size, lightweight DC motors, which are currently used for vibration of cellular phones. Solenoid type consists of six tubular solenoids weighting 15 grams each. Each device is fixed onto the setting of the ring. Thereby the palm can be used freely and the device never prevents the user from obtaining original tactile sense information. The initial version of this prototype connects to a parallel port, and the improved version connects to a USB port. Each device is connected to a wearable computer, so that Deaf-Blind people can use it in their daily life. In order to support the wearable computers with the Finger-Braille device, the authors designed and implemented an outdoor ubiquitous experimental environment for barrier-free applications:

This environment consists of wireless LAN networks to support communication links among wearable computers, access boxes called hard-points to support net-

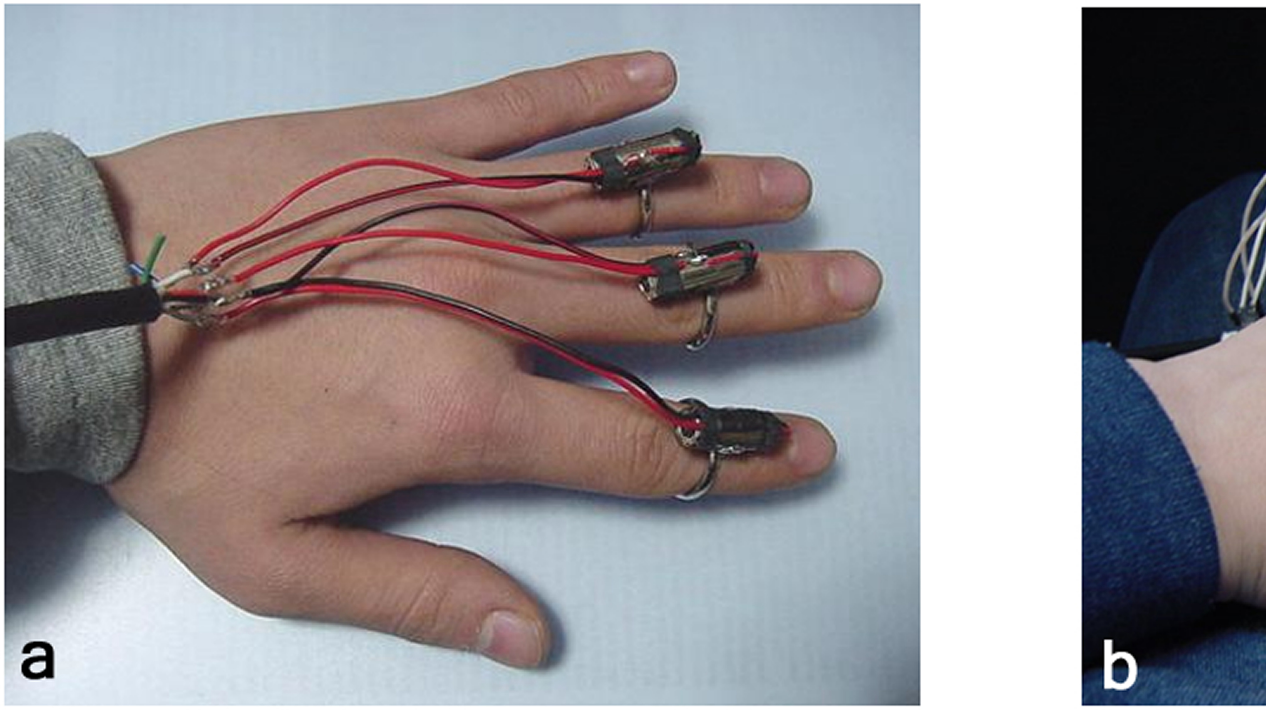

Fig. 22: Wearable Finger-Braille Interface

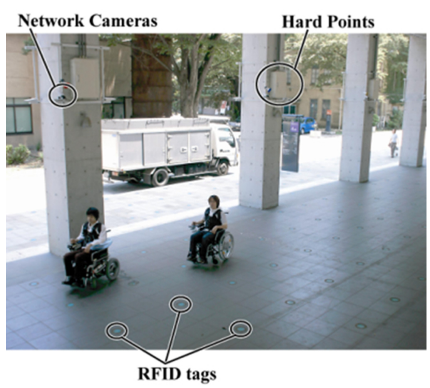

Fig. 23: Outdoor Barrier-Free Experimental Environment

work connection and power supply, network cameras to observe users behavior and floor-embedded active RFID tags to detect the users position.

2.4 Devices for interaction with everyday objects Here we consider some examples, based on scientific studies, of how assistive technologies may assist people in the interaction with everyday objects.

3.3.4 Ubi-Finger

Ubi-Finger [62] is a compact gesture input device attached on fingers. It realizes sensuous operations of various devices in real world with gestures of fingers. The main concepts of Ubi-Finger are as follows. ? sensuous operations with gestures of fingers; ? wearable interface optimized for mobile use; ? multiple uses with a single interface. By using Ubi-Finger, users can control various devices in real world simply and sensuously: a user can select a target device by pointing it with her/his index finger and send her/his ID via infrared. Then, a user can control the target device with gestures of fingers: since she/he has selected the target device previously, the control methods don't become complicated regardless of increase of target devices. The device architecture of Ubi-Finger consists of three sensors (a bending sensor, an acceleration sensor, and a touch sensor) to detect gestures of fingers, an infrared transmitter to select a target device in real world and a microcomputer to control these sensors and communicate with a host computer:

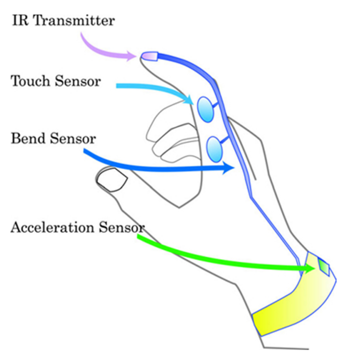

Fig. 24: Basic Concept of Ubi-Finger.

Each sensor generates the information of motions as follows: (1) a bending degree of an index finger, (2) tilt angles of a wrist, (3) operations of touch sensors by a thumb. They use (1) and (2) for recognition of gestures, and use (3) for the trigger mechanism to start and stop gesture recognition. The system architecture to control real-world devices with Ubi-Finger consists of four main factors: Ubi-Finger device, Ubi-Appliance (an information appliance with an infrared receiver, LEDs, and a network connection), Ubi-Host (a host computer of Ubi-Finger device) and Ubi-Server (a server to control Ubi-Appliance):

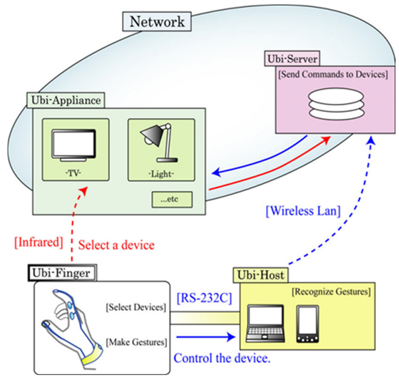

Fig. 25: System Architecture of Ubi-Finger.

First, a user points at an information appliance (Ubi-Appliance) with Ubi-Finger, and transmits her/his unique ID via infrared signal. When the Ubi-Appliance receives the signal, it transmits both its own ID and the user's ID to a server (Ubi-Server), and the Ubi-Server associates these IDs together to get the correspondence of the user and the Ubi-Appliance. Then, the Ubi-Server transmits a feedback signal to the Ubi-Appliance, and the Ubi-Appliance shows its state of selection with LEDs. After the user confirms the state of the target Ubi-Appliance, she/he performs a gesture with Ubi-Finger. A host computer (Ubi-Host) recognizes the gesture, converts it to a specific ID, and transmits it to the Ubi-Server with the user's ID. The Ubi-Server identifies the target Ubi-Appliance with the user's ID, converts the gesture's ID to an appropriate command for the Ubi-Appliance, and controls it via network. The size of the prototype device is as compact as a fingertip. The device architectures of the prototype are as follows:

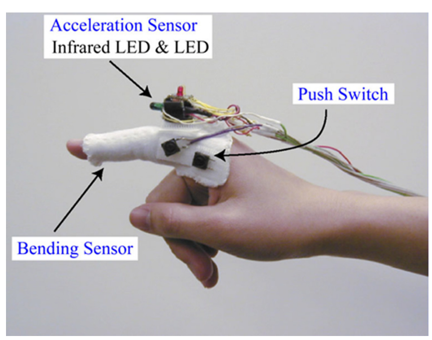

Fig. 26: Prototype of Ubi-Finger Hardware

They attached a bending sensor (BendMini by Infusion Systems) on an index finger and two compact switches on the side of an index finger. In addition, they have set a 2-axis acceleration sensor (ADXL202E by Analog Devices), an infrared transmitter, and two LEDs on the portion of an index finger. They used a microcomputer (Tiny-H8) to convert the information generated by the sensors to numerical values, and transmit them to a laptop computer. Then, the Ubi-Host software on the laptop computer recognizes gestures by analyzing the input value in real time, and communicates with Ubi-Server via wireless network.

3.3.5 FieldMouse

FieldMouse [63] is a combination of an ID detection device and a motion detection device. The first device can be a barcode reader, RFID tag reader, etc., and the second device can be a mouse, a gyroscope, an accelerometer, etc. With the combination of these devices, various real-world interactions become possible: users can control real-world appliances or program various information appliances just like performing GUI operations on graphical computer terminals. They have been developing various combinations of the devices. The first one is a pen-type FieldMouse which consists of a barcode scanner and a pen-mouse:

Fig. 27: FieldMouse 1: Combination of a barcode reader and a pen-mouse.

The second one is a combination of a pen-type barcode scanner and a mouse with a gyroscope:

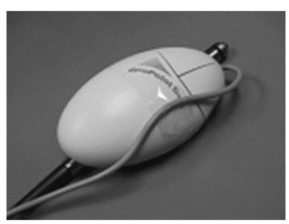

Fig. 28: FieldMouse 2: Combination of a barcode reader and a gyro-mouse.

A FieldMouse can use the barcode reader to tell what and where it is pointing at and measure the relative movement of the device after detecting the barcode. For example, to use a menu or a slider, a user first moves the FieldMouse to a barcode, clicks a button to initiate the scanner, waits until the barcode is recognized, moves the FieldMouse and releases the button. Since barcodes are usually recognized instantly, there is almost no time lag in the recognition step, and users feels little differences between using a mouse in a computer display and using a FieldMouse for using a menu or a slider in the real world.

3.4 Indicators and other signaling/alert devices

We start considering light probes that indicate the presence of light by a change in audio or tactual output. The most common devices use a photocell which controls the frequency of an audio signal; the pitch of the output is dependent on the amount of light reaching the photocell. A passive light probe reacts to external light sources, but the active type includes a light source so it can measure the reflectivity of a surface. Colour sensors are able to determine colours (usually from a pre-set range) and hues or shades of items of clothing, food and many other things. Most will often use audible voice output to impart this information. Some current colour sensors also have other functions ranging from light probes to alarm clocks. Liquid level indicators usually give an audible or vibratory indication of when a conducting fluid has reached a pre-set height. The most common application is for pouring cups of tea or coffee. If the prongs are not insulated, the device should not be used with a container which has a conducting rim (e.g. a gold-rimmed wine glass). Thermometers are needed for measuring temperature of cooking, industrial processes (e.g. photographic processing), human body (clinical thermometers) and room or outdoor ambient conditions. The thermometers in this section have audio output.

3.4.1 5DT Data Glove

Commercialized by Fifth Dimension Technologies (5DT) (Irvine, CA), it comes in several versions. The 5DT Data Glove [65] has been designed to satisfy the stringent requirements of modern Motion Capture and Animation Professionals:

Fig. 29: The 5DT Data Glove

The 5DT Data Glove 5 uses proprietary optical-fiber flexor sensors. One end of each fiber loop is connected to a LED, while light returning from the other end is sensed by a phototransistor. The glove measures finger flexure (2 sensors per finger) as well as the abduction between fingers. Gesture 0 is defined as all the fingers closed and gesture 15 as all the fingers open. In the 5DT Data Glove 5, a finger is considered unflexed/flexed if the sensor reading is smaller/greater than a predetermined lower/upper threshold.

4 Open Problems

Nowadays, given the statistics of the deafblind and the costs of learning touch-based communication systems, only a minority of people with normal hearing and vision know tactile languages (see Section **??**). This is because of personal factors (e.g., some of their relatives are deafblind) or because of their jobs (e.g., assistants). As a result, touch-based communication systems are basically known by primary users (i.e., blind, deaf, and deafblind), by their family (or their close milieu), and by their assistants, only. In order to communicate with individuals that use tactile languages, people with normal hearing and sight who are not able to utilize any touch-based communication systems require the constant presence of an interpreter who has the purpose of translating communication from the tactile language to verbal communication, and vice versa. However, the main issue with touch-based communication systems and, in general, with Augmentative and Alternative Communication systems (AACs) is that, as they are not widespread in the community of non-impaired people, they require the deaf, blind and deafblind to need the constant presence of an assistant who plays the role of an interpreter in situations of interpersonal communication. This, in turn, poses strong limitations to their opportunities in terms of interaction with the external world. Moreover, as there are no official models to conceptualize touch-based communication systems, it is extremely difficult to learn such languages.

Two aspects have to be considered at the beginning of the process of introducing novel devices in the field of assistive technology, and specifically, structural (i.e., market) and functional (i.e., technological) barriers. The former are related to the scenario of technology for needs and, specifically, to highly customizable assistive technology, which has a different set of features with respect to other markets. Additionally, there are technological challenges related to the design and development of novel devices targeting individual needs, which have to be addressed with methods that are able to cope with the special requirements of end users.

The structural barriers to innovation in niche markets such as that of the deafblind include the following:

- **Limited support from public health** is an umbrella comprising a large set of issues. Despite research and development of assistive systems are highly encouraged by government, they receive limited financial support with respect to other sectors that are considered with much priority. This is the main cause of a major lack of coverage for equipment that could help develop products and services that could benefit people with impairments. Despite some research programs fund research at a national level, governments mainly apply a reactive approach and, thus, they are characterized as technology buyers. However, they apply restrictive funding policies for durable medical equipment. In addition to financial issues, both medicare and medicaid lack vision about assistive technology. Consequently, the market has no institutional guidance, and it is driven by companies, who are responsible for interpreting the needs of final users. The absence of a top-down approach increases fragmentation in the scenario of assistive technology, and it limits sharing best practices.

- As an additional challenge related to market fragmentation at the government level, each country has **different validation requirements** for approving the same technology.
- Companies usually receive and invest **limited funding in research and development**: although there is an increasing demand of custom and personal assistive technology, being a market extremely prone to risk, companies and investors prefer not to fund new technology, unless highly profitable, which is not the case of niche markets.
- *Ad hoc* technology suffers from **high vulnerability of patents**: custom-developed assistive technology having a few or no features in common lead to intellectual property that has poor reusability and, therefore, low value for companies that invest in research and development. This prevents many stakeholders to focus on this market.
- There is large debate on the **budget for purchase**, which essentially defines which are the stakeholders responsible for buying assistive technology. As each case is different, new companies willing to enter the market invest large amounts of money to identify their revenue model and to determine whether final the National Health Service, insurance companies, or individuals are the buyers.
- **assessment lacks of standards** that allow sharing results about the implications of the adoption assistive technology in terms of acceptability. In this regard, the Health Technology Assessment (HTA) is a step forward, though it is mainly applied to medical devices. Less attention is devoted to products, services, and best practice protocols that support individuals in their everyday tasks. Moreover, it is not possible to transfer knowledge about the application of a technology to different scenarios.
- **experts are not available** and so are professionals and para-professionals working in the field of assistive technology services, such as physical and occupational therapists, speech pathologists, physicians, nurses, aids, and other health professionals.
- **poor support** for family from the community of assistive technology experts.
- **lack of awareness** about the potential of technology and its adoption process. In general, patients, people with disabilities and the elderly, including their families,

and professionals assisting them have limited access to accurate and up-to-date information about assistive technology devices and services.

Indeed, in addition to the aforementioned items, there are other deleterious factors that apply to specific circumstances. In order to deliver innovation in niche markets at a rate comparable with that of other types of markets, novel design and development methodologies are required to cope with the limitations posed by the inherent characteristics of any niche market itself. New approaches based on participation can change the way in which innovation is conceived, in order to save money and time, and to advance technology in a sustainable fashion.

In addition to structural bariers related to the way in which the market of assistive technology operates, there are technological issues related to the design and development of solutions that have to fit the diverse needs of different people having special requirements. Indeed, high levels of discontinuation are found in standard technology that does not adapt to users' needs. Therefore, one of the main challenges with respect to acceptability and adoption of human-computer interfaces (and, in general, technological devices) is the adaptability of the solution to the specific situation to which it will be applied. This is particularly true in assistive devices, because they have the role of supporting people living in diverse conditions, and affected by different impairments.

Usually, the majority of custom assistive technology are developed in laboratories and in small research centers. The largest market of assistive systems, that is, prostheses, makes no exception, as they need great adaptation to subjects' physical characteristics. Therefore, people have to visit development centers in order to get their prosthesis customized for their needs. Indeed, the cost of travel is worth the benefits of an effective and functioning aid. However, in other market verticals, and especially if products target more specific impairments, the process is less standard. The more devices are designed *ad hoc* to cope with specific requirements, the more different pieces of technology are utilized. As a consequence, in addition to market fragmentation, there is high diversity in the design of assistive devices. Also, being a niche market with limited number of users implies poor communication among laboratories and companies doing research on similar issues.

The systems presented in this chapter are not suitable for our problem because:

- many of the evaluated devices are still in an experimental stage, so they don't yet have a market and therefore they haven't reached an industrialization stage;
- they don't support mobility, binding the user to a fixed position or are too bulky and difficult to carry with them;
- for those devices based on communication languages, many of them using communication languages that are difficult to learn and therefore such devices, in general, are difficult to use;
- some of them are too expensive (for example, the Braille readers);
- other are not compatible with other devices (such as smartphones);

In this regard, a participative approach to the design and to the development of assistive devices may be a solution. Participatory design is a major topic in the scientific community and specifically in the field of human-computer interaction, especially in the domain of software development. However, software benefits from being immaterial and thus, in the design of software systems, there are several solutions for achieving distance collaboration, parallel development, task management, and team synchronization based on Collaborative Work and Communication Systems (CSCW) tools. Conversely, dealing with hardware has several limitations due to the presence of physical objects that have to be manipulated, refined, and exchanged.

As a result, remote collaboration in the design and development of hardware is known as being affected by poor scalability. Specifically, as assistive devices require particular attention to several crucial features, for hardware interfaces, meeting the requirements of software systems in terms of user participation is almost impossible. As a result, the production of assistive solutions is either extremely customized, that is, *ad hoc* (and, therefore, very expensive), or completely standardized and less adaptable to the needs of final users. Consequently, there is a number of effective *on-demand* solutions tailored for the needs of specific people, whose characteristics are difficult to implement in industrially-produced devices. Moreover, there is a missing link between systems realized with a participatory approach and standards in the industrial production of devices. Consequently, there is high fragmentation in the scenario of solutions for people with disabilities, where it is necessary to aggregate development standards and customization techniques.

4.1 Current and future work

Several aspects of our research could not be incorporated in the current dissertation because they are beyond the focus of computer engineering. Specifically, we designed a participatory development process for including remotely-located end users in the design of their custom interfaces. Our proposed methodology provides customers with paper-and-scissors tools for refining the pad of dbGLOVE so that it perfectly fits the deafblind's hand. In addition to increasing comfort, our technique enables saving production and maintenance costs. Also, we defined an innovative (patent pending) business method for penetrating the market of assistive technology dedicated to people with sensory impairments using practices that engage users and may help reduce the discontinuation rate.

This dissertation describes part of the research realized along the path of an entrepreneurial project aimed at disseminating innovation in the market. In addition to a businesswise point of view, this will be beneficial for our future research. Particularly, we will continue the investigation of sensory dynamics of people with visual and hearing disabilities. The majority of the work on dbGLOVE will regard the implementation of communication methods that simplify input and increase the accuracy of output. The basis for smart input techniques has been introduced in part II.

5 Future Outlook

Therefore, the research described in Part II is completely focused on natural interfaces having high acceptability and low cost. The development of dbGLOVE required several years of work in the field that allowed us to identify the very specific communication needs of the deafblind using the Malossi alphabet. As a result, we designed a wearable interface based on a language invented by a deafblind. dbGLOVE requires no additional effort to the deafblind who already know the language. Our studies demonstrated the effectiveness of our devices in granting bidirectional communication with a much lower learning curve with respect to the Braille system, enabling the deafblind to achieve language proficiency comparable to standard keyboards in terms of speed and accuracy. One of the most frequent scenarios in centers devoted to sensory-impaired people involves assistants using several communication systems in order to exchange messages with different users who are deaf, blind, or deafblind. Moreover, caregivers use different methods for interacting with individuals depending on the specific situation of each individual. For instance, the deaf would use sign languages, whereas blind people would speak and read Braille; on the contrary, others would use the Malossi alphabet or print-on-palm, depending if they are deafblind born or have become deafblind in their later life. On the contrary, sensory-impaired children would use objects for communicating, whereas adults with additional impairments at the cognitive level would exchange simple touch cues. It is impressive to see that, although different communication systems help people to interact with the external world, on the other hand, so many languages separate individuals living in the same environment, sharing the same space, and experiencing similar conditions. Nevertheless, regardless of their specific situation, generally, sensory-impaired people are not able to interact with people other than assistants, family members, or close friends who know their language.

Knowing individuals' characteristics and languages, assistants can switch from one communication system to another in order to cope with different requirements and sensory impairments. As a result, they enable communication in a peer to peer fashion. However, they can serve one user at a time, and their services involve additional costs many are not able to pay for. Consequently, they are available for limited time. We envision a system that plays the role of an assistant in interpreting communication from different touch-based systems to written or spoken language, and vice versa. Thus, they enable individuals to autonomously communicate with sensory-impaired people, allowing each to use their own language, without requiring them to learn others' languages. Moreover, rendering communication systems interoperable would help sensory-impaired people interact with the external world, be autonomous and independent in communication, get access to information, and achieve social inclusion.

Although they can easily be formalized into a set of patterns that would simplify their utilization, as Augmentative and Alternative Communication systems represent niche markets, they receive less attention. Consequently, there is poor interoperability between interfaces and assistive devices adopting different languages. Also, this affects the development of new communication technology for the blind, due to increased costs, difficulty in accessing to resources, and lack of scalability. Furthermore, this is the fundamental reason why design patterns, which are widespread in the community of Human-Computer Interaction, are not available in the domain of assistive technology.

Patterns and frameworks are among the most powerful methods for approaching to the design of new solutions. The former consist in couples of items, one representing a typical design issue, and the other element representing a set of key insights to the solution. The latter are conceptual models of a domain that help organize and manipulate knowledge effectively. Both have widely been employed in the development of software systems, and they have been utilized in other domains, such as architecture and engineering, for decades. Patterns and frameworks provide designers and developers with robust solutions to recurring problems, and they allow consistent communication between operators focusing on the same field of study. Moreover, frameworks offer an interpretation tool for new issues, because they can offer an insight to previously adopted methods, they allow to programmatically review the state of the art, and they help anticipate new circumstances. Despite the benefits they may have in the domain of assistive technology, there are only a few conceptualizations, and they mainly focus on the assessment of technology, that is, they regard at the very last stage of the development process. Although they are crucial, proactive frameworks for supporting the initial stage of the design of innovative solutions would be of more support, because they would help close the loop with frameworks that examine assistive technoloy in a reactive fashion.

Several organizations designed and developed frameworks for Augmentative and Alternative Communication systems. Among them, the Daisy consortium is at the most advanced stage, as they are the responsible for the ANSI/NISO Z39.98-2012 Standard, i.e., *Authoring and Interchange Framework for Adaptive XML Publishing Specification* [**?**]. This, in turn, defines a framework in which to develop XML markup languages to represent different types of information resources (books, periodicals, etc.), with the intent of producing documents suitable for transformation into different universally accessible formats. The standard focuses on accessible output requirements, with the aim of rendering information resources accessible both using current e-book readers and with Braille displays. However, it does not take into consideration communication between individuals, or interaction with a computer.

In this section, we introduce a conceptual framework for the interoperability of touch-based communication systems. Also, we detail a meta-language for describing the so-called Augmentative and Alternative Communication systems [?] based on touch, with the objective of producing their formalization. Moreover, we review the major touch-based methods for exchanging information with the external world, with the purpose of describing their implementation in our proposed framework. Indeed, as the development of standards is an evolutionary process, we introduce some of the elements that aim at giving examples for further research and applications.

5.1 Framework architecture

We propose an interpretation framework for touch-based languages that focuses on the use of technology for interpersonal communication. Although we specifically refer to computer-mediated interaction with the external world, the results can be reused in other domains. To this end, we designed our framework to be compatible with current standards and, specifically, with [?]. Our framework aims at standardizing the way in which different pieces of assistive technology are employed with respect to the languages already known and utilized by their users. The ultimate goal of our framework is to render assistive technology interoperable. To this end, we avoid defining models and architectures for markup languages. Instead, we focus on a general, extensible and highly-adaptable structure in which specific models can be defined. We provide example implementations of several different languages with the only purpose of demonstrating the feasibility and the applicability of our framework to a variety of communication systems, thus, supporting the diverse requirements of blind, deaf and, particularly, deafblind people.

Therefore, our framework conceptualizes touch-based communication methods, and it defines the main architectural requirements for the interoperability of communication technology for people with special needs, without specifying the low-level rules and requirements for the implementation. Particularly, the architecture defines the components that support communication in case assistive technology is employed, but it does not define any rules for describing how messages are exchanged. As in the case of low-level implementation, this is a matter of further standardization.

The primary objective of the proposed framework is to support the development of technology for sensory substitution, by encompassing the alternatives to vision and hearing in a flexible and versatile fashion. Also, it enables the design of new training tools for enabling people to learn and use touch-based communication systems. The proposed framework is particularly suitable for situations in which individuals in different conditions want to interact, each using their own language and device. By defining a model that incorporates and implements several communication methods, it is possible to design an interpretation system that enables the automatic encoding and decoding of messages taking into consideration and adapting to individuals' diverse needs.

Computer-mediated communication based on touch that occurs between two individuals includes the sender and the receiver of the message, the devices through which messages are sent and received, the communication systems (which can be different) utilized by the sender and the receiver, the protocols that rule communication, and the context in which interaction occurs. As a result, the proposed framework consists of the following components:

- *agents*, which represent the humans (or machines) involved in communication, that is, the senders and the receivers of messages;
- *protocols* and languages (rules, conventions, and meanings) that are employed for encoding and decoding messages from one language another, in a bidirectional fashion, and for interpreting them into executable actions, starting from sets of symbols that encode and decode messages;
- *devices*, representing the technology employed to support communication via perceptual channels (i.e., sight, audition, touch); in general, we will refer to touch-based communication systems;
- *contexts* in which communication or interaction occurs; also, this defines states, actions and conditions that affect or rule the functional goals of communication.

Figure **??** depicts the architecture of our system. The sender and the receiver are the two endpoints of communication. They may be in or refer to different contexts (see Section **??**), they may use different languages and different pieces of technology. For instance, sighted senders would type their message in written English using a keyboard, while deafblind receivers would read the message in Braille on a dedicated display. Also, the former could be using a mobile Application, while the latter could be sitting in front of a computer, at a community center. In our framework, language is incorporated into the device. Although this might seem less user-centric, it actually helps represent devices as natural interfaces: they should inherently implement the language already in use by individuals, without requiring users to adapt to technology. Protocols allow functional communication between the sender and the receiver by mediating their messages. The communication protocol is responsible for encoding and decoding message content from one language to another.

Contexts, protocols and devices should be invisible to users, as they are implicit, transparent, and natural, respectively. Specifically:

- *as interaction is situated,* ***users manifest the context in which they operate***: characteristics of individuals' background are defined within instances of user models;
- ***messages are proximal representations*** *of distal intentional meanings*: in the exchange of messages between the sender and the receiver, the syntactic content is the only part to be translated (i.e., encoded or decoded), whereas the semantic component should remain unchanged;

- *as they are natural interfaces,* ***devices expose communication systems without additional overload***: although users interact with tangible technology, they should keep using their language of preference with little or no modification.

As a result, contexts refer to different situations in which individuals may interact with devices (how communication changes depending on the circumstance), protocols regard to the way in which the content of messages are syntactically and semantically structured (how communication is defined by the language), and devices implement the interaction dynamics of languages into technology for communication (how languages are enabled through technology). The latter will be discussed in Section **??**. This section focuses on language modeling of touch-based communication systems.

5.1.1 Agents as mediated communication endpoints

In the majority of computer-supported communication, there are two human endpoints mediated by a machine agent, who plays the role of an interpreter. Also, there are circumstances in which users interact with computers, only, which is especially the case of getting access to information. The basic difference between the two situations is in the decoding function, which is left to the receiver in the former case, while in the latter, messages sent by the user have to be interpreted a commands by the machine. Despite the complexity of interpreting users' commands, which also depends on the interaction context (see next section), mediating interpersonal communication is more challenging, as individuals in different situations have diverse needs. Usually, it is assumed that the two communication endpoints utilize the same communication channel (e.g., speech), the same language (e.g., written English), and the same communication device (e.g., voice, or keyboard and screen). Conversely, individuals suffering from sensory impairments need to interact with people having normal sight and hearing, in most of the circumstances. To this end, either the former require the latter to know their communication method, or they need the presence of an interpreter who translates messages for them. Moreover, assistants are needed for interacting with the environment and with the external world. In this regard, methods for exploring the ambience usually have a human communication endpoint, though the environment itself can be conceived as a communication endpoint.

In this dissertation, we will not focus on the conceptualization of agents. Several representations are available for describing human and virtual agents, as well as their characteristics and requirements, and any user model of choice can be incorporated in the framework. As the focus of this dissertation is capturing how communication systems can be mediated by computers in order to be interoperable, we will conceive the sender and the receiver as users of devices each incorporating a communication system. As a result, users can be described as a set of preferences with respect to the languages they know, to the devices they utilize, and to the contexts in which they are. By doing this, it is possible to adapt the specifications of the components of the framework to the different user profiles, and to obtain a fine-level description of language preferences, context intents, and device configurations.

5.2 Modeling functional communication by means of protocols

In our framework, we focus on the basic form of communication, the so-called *functional communication*, in which language is simply functional to modifying the environment in a way useful to the sender (or to the receiver) of the message. It is said *functional* because its purpose is in that the result of communication can be predictable or controllable (in some sense) by the sender. A communication system is (said to be) functional if the both of the following hold:

Moreover, functional communication is *intentional*, that is, messages are transmitted on purpose from the sender to the receiver. Functional communication is based on two main functions:

Although it may seem extremely basic, functional communication plays a crucial role for people with impairments, and especially for those who are not independent. As many of them rely on the presence of others to realize even the most elementary actions, being able to communicate their needs helps them achieve their goal.

In our framework, we model functional communication using Finite State Machines (FSM): it can be regarded as a set of *input events* (i.e., messages) that allow individuals to activate *state transitions* (i.e., actions) that, depending on certain *conditions*, enable switching the *states* in which individuals can be (e.g., thirsty, tired, hungry). Thus, functional communication refers to a system having a limited number of defined states, and specifically, need (e.g., urgency to go to the toilet), emergency (e.g., having an epileptic shock), or information (i.e., interpersonal interaction or access to information resources). Figure **??** represents the three circumstances. In this case, we refer to the semantic component of messages (i.e., the intent), that allow others to interpret individuals state and to perform actions accordingly. Consequently, at a semantic level, messages are requests for actions defined by means of syntactic structures in the language of choice.

In our framework, languages are conceived as syntactic means for encoding intent. Moreover, as basic communication has the purpose of providing people having cognitive disabilities with a way to exchange functional messages, it requires the receptive and the expressive functions to use *transparent language codes*, that is, the *sign* and the *significant* (in semiotic terms) should have the least cognitive distance possible. In other words, basic communication aims at reducing the cognitive distance between the symbols and the subjects, the objects or the situations they refer to.

In basic communication, there is direct correspondence between semantics and one specific level of the language model (see Figure **??**), without any further separation or additional specification. The syntactic layer can be represented by morphology, articulation, or lexical layer. Pragmatics play a fundamental role in disambiguating the meaning, so that the same articulation might be associated with different meanings, depending on the situation.

5.3 A hierarchical model of human language

The language component of our framework incorporates the basic structures that enable operating with different touch-based communication systems having heterogeneous features. Although there is an open debate on the model to be utilized for representing the human language, we employed a hierarchical structure. Basically, this is for simplicity in the description of the model, extensibility, and compatibility with the other components of the framework. In this paragraph, we introduce our model and we detail both its design and its implementation.

Actually, the human language inherently contains some form of hierarchical organization, as elements at one level (e.g., letters) are the foundation for the next level (e.g., words). Usually, layers are connected by means of causal or constructive relationships (e.g., letters are utilized to compose words). Also, there are different relationships that enable bidirectional connections between layers. Elements at a upper level constrain elements at the lower level, and vice versa: lower level elements are the necessary units of higher levels (e.g., words cannot be structured without letters); on the contrary, elements at higher levels determine the way in which lower level items have to be utilized in order for messages to be functional from an expressive point of view (e.g., words define the sequence in which letters have to be assembled in order to be significant). As another example, syntax rules over words, specifying how these can be combined in order for messages to be correct; simultaneously, syntax would have no meaning without the presence of words, which are the fundamental elements of sentences.

We modeled human language as a structure consisting of six nested layers, where each is a collection of homogeneous elements. Figure **??** shows a graphical representation of our language model. The five innermost layers (i.e., morphology, articulation, lexical, and syntax) incorporate the structural features of the language, whereas the two outermost layers (i.e., semantics and pragmatics) are more related to interpretation and meaning, and they include the functional desired outcome of any intentional communication. In our model, hierarchy is flexible, in the sense that the boundaries between levels can be adjusted depending on the communication intent and situation. Also, levels can be merged or removed depending on the complexity of the language. The only constraint is the presence of at least one structural layer and one functional layer. As the main objective of our model is to support functional communication (see previous section), we modeled language in order to primarily accomplish functional tasks. Therefore, we do not take into consideration more general-purpose semantics. Our proposed language hierarchy consists of the following layers:

1. *morphology*, which refers to atomic components of speech; in the case of spoken languages, this is the set of atomic sounds that compose the language, whereas in the case of gestural languages (such as fingerspelling), it is the set of basic configurations of the hands;
2. *articulation*, representing elementary combinations of morphological elements (e.g., letter and sound), such as complex gestures realized by sequential or simultaneous individual configurations;
3. *lexical*, including the set of individual words that are composed by multiple morphological symbols or articulations;
4. *syntax*, referring to the process by which words are combined together to form correct sentences that can be interpreted;
5. *semantics*, which refers to the functional outcome of intentional communication with direct links to the actions that have to be realized in order to accomplish the objective (e.g., messages, such as *I need water* or *I am thirsty* should activate the same action in the receiver, i.e., *bring water*, in order to move the sender to the state *I am ok*);
6. *pragmatics*, that is, the actual actions to be realized in order to satisfy the needs expressed by semantics.

The above categorization can be applied to spoken, visual and tactile languages, that is, it is independent from the communication channel being utilized. Also, it can be extended to encompass more layers (e.g., the discourse layer, which refers to large groups of sentences) in order to support more sophisticated applications. Moreover, the language model can be utilized in other scenarios and domains that are beyond the scope of this dissertation.

6 References

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