Enabling Touch-Based Communication in Wearable Devices for People with Sensory and Multisensory Impairments

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Abstract. Tactile signing and touch-based alphabets are among the primary communication systems for people who suffer from sensory or multisensory conditions, such as, blindness or deaf-blindness, respectively. In the last decade, several research projects based on sensory substitution focused on developing novel interfaces. However, people who are sensory-impaired still lack reliable technology for interacting with the world. To this end, wearable devices could have a significant role in providing individuals with support for daily activities, communication, and social inclusion. In this paper, we introduce a categorization based on technology for sensing and representing the main components of touch- and gesture-based communication systems (i.e., movement, gesture, pressure, and touch) to provide an understanding of the technical and human factors which affect or foster the development of new assistive technology.

Keywords: Deaf-blindness · Sensory substitution · Touch-based alphabets · Tactile languages · Wearable devices

1 Introduction

People who are blind or deaf rely on sensory replacement to compensate for their condition, and to interact with the world: hand-based communication techniques, such as Braille or sign language, are among the most common forms of communication for the blind and the deaf, respectively, in addition to residual vision or hearing.

Conversely, individuals suffering from multi-sensory impairments primarily use touch to communicate. Touch cues are the basic element of functional communication, which is utilized for expressing simple needs, concepts, and sensations. Also, advanced tactile signing techniques and tactile alphabets, such as, the deaf-blind manual, Lorm, or Malossi, are widespread among people who are deaf-blind, though their communities are organized in niches in which small groups develop, use, and share their own communication systems.

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In the last decade, several tangible interfaces explored touch-based communication as a way to transmit tactile sensations remotely [1]. Also, recent devices introduced the possibility of incorporating touch-based languages into wearable technology in the form of gloves to help the deaf-blind interact with the world [2–4]. However, lack of attention to human factors led to demonstrators with little usability, to prototypes having poor acceptability, and to individually-crafted pieces of technology which are not suitable for manufacturing. Consequently, even the most developed technology for the largest group of people who are affected by sensory conditions, that is, Braille displays for the visually impaired, is available to 5% of the blind population, only, due to its requirements and costs, and to poor literacy [5]. Situations in which multiple sensory impairments occur show lower rates due to additional issues (e.g., cognitive conditions). Indeed, especially in the field of assistive technology, ergonomics play a crucial role in regard to usability; in addition, the degrees of freedom of the hands inherently involve major design challenges. Furthermore, industrial manufacturing poses additional constraints, though it offers valuable insights into the feasibility of specific solutions, and it suggests improvements to the design patterns.

In this paper, we focus on the design glove-based assistive technology for people with sensory and multisensory conditions, and we discuss its challenges from both ergonomics and feasibility perspectives. To this end, we detail the dynamics of touch and motion cues involved in tactile signing techniques and alphabets, in order to categorize them with specific regard to their implementation in wearable technology.

In particular, we identify the four basic components of hand-based functional communication and tactile languages, that is, motion, gesture, pressure, and touch; we discuss how they can be leveraged to encode information, from concepts to words and letters. Also, we describe the implementation of the four basic components into wearable devices by means of different types of sensors and actuators. Moreover, we review current wearable technology for enabling people with sensory and multisensory impairments to communicate, and we analyze their pros and cons in regard to usability and feasibility.

Furthermore, by taking into account additional human factors in the use of tactile languages (e.g., dialects, abbreviations, personalization of gestures and touch cues, and role of individuals' milieu), we address the dynamic complexity of the adoption of glove-based technology from technical (both hardware and software) and ergonomic perspectives, from qualitative and quantitative standpoints.

Finally, we evaluate and suggest several design patterns for incorporating touch-based communication systems into viable hand-based devices. By doing this, we aim at providing a better understanding on the development of new glove-based devices, at offering insights on how to improve existing solutions, and at fostering a more user-oriented approach in the design of wearable assistive technology.

2 Modeling Tactile Languages

In order to evaluate technology and techniques for sensing and representing touch-based alphabets, we identified the main components involved in the representation of languages in tactile form. Indeed, we can describe all tactile languages and touch-based alphabets as consisting of sequences of symbols based on touch cues. However, they significantly differ from one another in components, such as, structure, representation, type of actions, and informative content. For instance, Braille utilizes small blocks incorporating six tiny dots that can be perceived using the fingertip of the index finger; sign languages involve different configurations of the hand and their position with respect to the chest, the head, and other areas of the body, and they convey the meaning of words and concepts; tactile signing utilizes the surface of the palm and the back of the hand as a space for representing letters by drawing a shape; the Malossi alphabet utilizes specific spots of the palm which can be pressed as in a typewriter.

We categorize the majority of tactile languages as based on three types of actions, that is, gesture, pressure, and touch. The former consists in peculiar configurations of the body and, specifically, of the hand; pressure involves stroking, pushing, or tapping on a smaller area of the body; the latter consists in smooth differences within a tiny portion of space, such as, the texture of a surface, which require fine perception. They are described in detail later in this Section, and they primarily consist of a static configuration (e.g., dots in Braille). Additionally, symbols can be represented by gestures and cues having dynamic components (e.g., touch cues in the deaf-blind manual). As a result, movement can be regarded as an essential part of the alphabet which can span across gesture, pressure, and touch, as an additional layer. This distinction is consistent with the approach adopted by Pederson: in [6], he introduces the egocentric interaction model, in which concentric circumferences are defined based on the distance from objects and on the type of interaction (i.e., observation, manipulation) that can occur in that specific portion of space.

From an interaction design standpoint, touch-based communication can be regarded as consisting of three different systems of actions occurring at a different scale of the human body. For instance, let us imagine a third observer located in front of two individuals communicating using different touch based languages. Gestures involve configurations of the whole hand; usually, the whole upper part of the body participates in the delivery of a specific meaning, also. Consequently, gestures are visible and they can even be understood from some distance. This results in an interaction area which is a 3d space that can be modeled as a cube having sides of approximately 1 m each. Conversely, pressure cues are realized on smaller portions of the body (usually the hand); although the observer would see that the individuals are exchanging messages in tactile form, he/she would be able to visualize tactile cues without any possibility of understanding the content of the messages. Pressure utilizes an interaction space which is smaller compared to gesture. It can be modeled as a bi-dimensional surface over the skin (e.g., over the palm or the back of the hand) having the size of a sheet of letter paper. Finally, a third observer would neither see nor catch any communication occurring via touch cues, as they are realized in a space which is smaller than the fingertip. Usually, communication via touch cues can be modeled as a one-dimensional space, because its atomic components can be represented on a single line. Figure 1 shows the interaction space in which the components of touch-based languages are located.

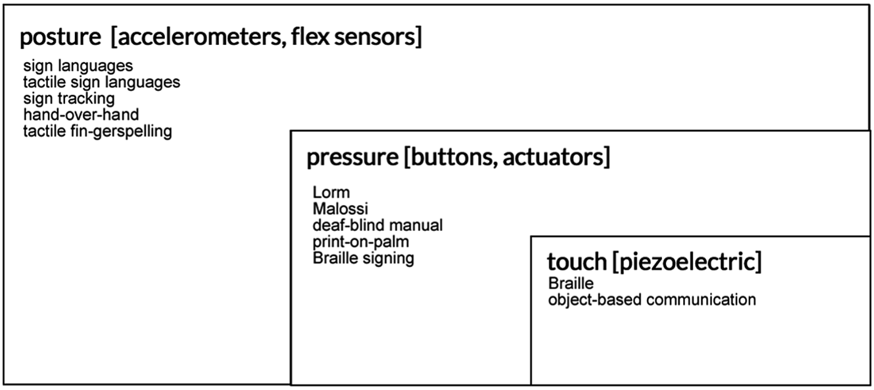

Fig. 1. The main components of tactile cues, and their hierarchy in space.

Categorizing languages into their tactile components has several advantages, as it enables an easier classification in terms of technology for sensing and representing tactile cues, and it supports the definition of common design principles. Also, as shown in Figure languages can be grouped with respect to their components: there is strong correlation between language clusters, interaction spaces, type of interaction cues, and sensors and actuators which support acquiring and representing their components. Tactile communication systems based on languages include sign languages and their modifications, including adapted sign languages, tactile sign languages, sign tracking, hand-over-hand, and tactile fingerspelling; conversely, languages which rely on pressure cues include speech-reading techniques, such as, Tadoma, or on-body signing methods, such as Lorm, Malossi, deaf-blind manual, print-on-palm, and Braille signing; finally, touch cues are utilized in Braille and in tactile symbol systems which utilize specific textures and patterns in the surface of objects to represent concepts.

As shown in Fig. 1, there are no intersections between languages, which results in a better distinction in terms of sensors and actuators supporting their implementation. Nevertheless, our categorization includes infrastructure-based devices, such as [7], or [8, 12], which use a webcam and Leap Motion, and Microsoft Kinect, respectively, to acquire gestures and translate sign language into text. However, in this paper, we focus on wearable interfaces, only, and particularly, on glove-like devices. As a result, infrastructure-based systems are beyond the purpose of this work. Although we discuss only a small niche of the large ecosystem of assistive technology, our findings can have a broader impact on other fields.

3 Sensing and Representing Touch-Based Alphabets

In this Section, we focus on the interaction components of languages (i.e., gesture, pressure, touch, and movement) and we discuss their implementation using technology for sensing and representing stimuli in the tactile form. To this end, we review the literature and identify common issues and potential solutions.

3.1 Gesture

Gesture refers to the static configuration of the hand, mainly represented by its components: orientation over three axes, that is, 3 degrees of freedom (DOF), flexion/extension, abduction/adduction, and supination/pronation of the wrist (3 DOF), and flexion-extension of the five fingers, each having 4 DOF (except the thumb, which has 5 DOF) [9]. As a result, the gesture of the hand alone has a total of 27 degrees of freedom. For the purpose of this work, we will consider movement as a separated from gesture, and we will focus on the static component of gestures. As 27 DOF pose important challenges on hardware and software development, the majority of projects limit orientation to 3 degrees of freedom, by eliminating the wrist, and by considering the palm, only. To this end, the main components for sensing gesture are inertial measurement units (IMUs), which became a standard thanks to the development of miniaturized sensors that were included in smartphones and immersive head-mounted displays. IMUs acquire the components of movement over each axis using a combination of accelerometer, gyroscope, and magnetometer, thus, leading to a total of 3 to 9 DOF. This strategy is utilized in [10, 11], and in many different research papers, which mainly describe interfaces supporting sign languages. Indeed, both the literature and commercial devices demonstrated that IMUs are the most appropriate equipment for sensing orientation and acceleration of the hand. As the interaction space in which gestures are realized is always aligned with the frontal panel of the individual, any movement has a relative orientation. Therefore, 6 DOF (accelerometer and gyroscope) suffice for detecting movement. Nevertheless, adding magnetometer enables additional significance and interaction opportunities which goes beyond tactile languages; for instance, a magnetometer-equipped glove can be utilized in combination with GPS sensor and data to provide individuals with information about the surrounding environment when users are pointing their hands towards a specific building.

As regards to movement of fingers, a large amount of work realized in the Virtual Reality can be leveraged for enabling gesture-based communication. There are two prominent types of technology can be utilized for acquiring fingers' movement: flex sensors and inertial measurement units, which represent the gesture of each finger using 1DOF and 3–9 DOF, respectively. Although they support detecting flexion/extension and adduction/abduction, each phalanx has 1 degree of freedom (i.e., flexion/extension), leading to 4 degrees of freedom of each finger (the thumb has 5). Consequently, precise detection would require incorporating arrays of 4–5 sensors for each finger. As a result, accurate recognition of the movement of phalanxes can be realized with expensive equipment, only. Nevertheless, the majority research studies considered 1DOF as enough for recognizing all the possible configuration of a single finger in almost every existing language based on gestures. The authors of [13], coherently with several research papers, incorporated flex sensors in wearable gloves for the recognition of sign languages. Usually, five sensors are mounted on the back of the hand. Although this positioning avoids having sensors on the palm and, thus, does not interfere with grasping, it leads to several issues in producing industrial products, mainly due to the mechanical stress insisting on different areas: the proximal part of sensors, that is, where they are soldered to the rest of the device is subject to rotation during adduction/abduction, and to increasing stretching during flexion; also, the area between the proximal and the middle phalanx is critical, because it forms a sharp angle wider than 90° during flexion, which, in turn, affects the accuracy of the sensor.

A different approach was adopted by [10], in which a device incorporating surface electromyography (sEMG) sensors capture electric signals which can be analyzed to decode the degree of flexion-extension of fingers with some degree of accuracy. Nevertheless, they show low reliability in recognizing fine movements of fingers, and thus, they are not suitable for representing sign languages in which there is a rich variety of gestures, because they would require extensive effort for disambiguation. Therefore, the most suitable devices for sensing gestures are IMUs and flex sensors. However, further investigation about their accuracy, computational cost, mechanical reliability, ergonomics, and user experience is still required.

As regards to representing gesture, there are several limitations in reproducing gestures using wearable devices. As a result, the only attempts of actively displaying the configuration of the hand have been realized using motorized hands or robots [16], which are extremely expensive and, thus, not suitable for any actual context of use. Consequently, the majority of devices based on gestures are input-only.

3.2 Pressure

In our work, we define pressure as single or multiple cues which can occur – individually or in a sequence – on specific areas of the hand. Two main components of pressure can be modulated, that is, intensity and location, resulting in communication systems having 2 DOF. In [2, 4], the authors present two devices based on pressure cues which exactly reproduce the layout as defined in the Lorm and Malossi alphabets, respectively. However, they use location only, to simplify the implementation of their gloves. This is mainly due to the complexity of current pressure sensors, and of the difficulty of incorporating them within the very small area of the hand. As a result, three types of sensors have been proven to support recognition of pressure: tactile-feedback switches, capacitive sensors, and piezo-resistive sensors.

Also, the authors of [14] introduce an American Sign Language translator based on 8 capacitive touch sensors placed over the palm, and on the tip of four fingers. However, this results in modifying the alphabet, which involves additional training, longer adoption curve, and higher risk of discontinuation.

Moreover, several alphabets based on pressure (e.g., deaf-blind manual) include letters consisting of multiple simultaneous cues, multiple independent channels have to be defined for sensing input. In this regard, languages have three additional degrees of freedom, that is, simultaneousness, duration, and sequence of cues. The former refers to the number of locations that can be elicited at the same time; duration can be utilized to distinguish letters, such as, in the Morse code, or to represent icons and concepts; the latter is specifically utilized to represent concepts as shortcuts, or to discriminate among letters involving cues on the same space. Indeed, as incorporating sensors in viable glove-like devices has to take into consideration manufacturing issues, one-wire capacitive sensors still are the primary detection equipment, though they involve additional issues in terms of compensating for spurious signals due to interference caused by the hand.

In regard to representing pressure cues on the hand, the most viable approaches so far have been described in [2, 4]. Both introduce two wearable communication and translation devices for the deaf-blind incorporating a number of vibrating motors that can elicit tactile stimuli in the form of displacement over the surface of the skin. The Lorm glove utilizes one degree of freedom, only, that is, different areas of the hand are stimulated with the same intensity in order to reproduce tactile sensation. Conversely, the authors of [4] utilize two degrees of freedom: by adding intensity, they can represent up to 5 distinguishable pressure cues over the skin, and elicit different tactile sensations.

3.3 Touch

Touch is the least utilized tactile cue in communication, especially at the beginning of the training of a new language, because it requires individuals' perception to be accurate and trained. Despite the difficulty in recognizing different textures on a surface, Braille is the most utilized method for writing and reading, though according several studies on Braille literacy, up to 90% of people with sensory and multisensory impairments are not able to perceive or understand it and, therefore, are considered as Braille-illiterate. Unfortunately, not only tactile alphabets based on touch cues require very expensive hardware, it is extremely hard for users to finely control their touch in order to represent letters and symbols with one finger, only. As a result, languages based on touch use an array of pressure cues to both sense letters. This is compatible with the one-dimensional structure discussed previously. 6 to 8 buttons can reproduce Braille dots at a larger scale, and provide individuals with an easier and more reliable input system. Also, beyond piezoelectric cells in Braille displays, touch cues can be represented using large vibrotactile actuators each representing a dot in the Braille encoding system. As a result, all glove-based devices do not support touch sensations which exactly match the communication system of choice.

4 Human Factors

In the previous Section, we followed a merely mechanical approach to the implementation of tactile languages. Nevertheless, identifying hardware and software requirements and specifications would be sufficient to achieve a viable solution which matches the dynamics of the communication system of choice. Several research and commercial projects followed this direction and led to the development of demonstrators and prototypes which were utilized in controlled test environments, only. In this context, human factors have to be integrated as design patterns: as interaction in the context of disability is always situated, further investigation on common issues and on potential solutions can be realized. In this Section, we focus on the human factors which play a crucial role in facilitating adoption and in preventing discontinuation in the context of assistive technology.

4.1 Barriers to Co-design

Among the main issues in designing assistive technology for people with multisensory impairments there are demographic factors and, specifically, lack of census data and information about individuals' condition, and poor access to user groups. These, in turn, are inherently sparse and, thus, it is very difficult to reach them. Additional human factors involve limited communication and interaction, which affect participatory approaches to the design process. Large diversity between users, education levels, cognitive conditions, and willingness to collaborate, limits the design phase to a top-down activity, only. In this regard, there is a need for identifying and involving patient innovators, who made the difference in developing the first – and still the most utilized – tactile communication systems, such as Braille, Malossi, and Lorm.

4.2 Understanding the Context of Use

Especially if there are no additional conditions (e.g., cognitive disorders), people who are sensory impaired have a much wider and detailed set of needs and requirements with respect to other users in the context of disability (e.g., autism). Therefore, understanding the context in which they will interact with technology and the purpose for using assistive devices is among the most important activities. Specifically, in addition to basic communication needs, they have advanced requirements, such as independent access to information, training, socialization, and work. As a consequence, they have higher expectations about technology as an enabler.

4.3 Training and Frustration

People with sensory or multi-sensory impairments are a very sensitive population. As a result, we expect devices to work since their very first use, and to be 100% reliable. Prototypes and demonstrators frequently lead to frustration in their early adopters if they do not work as expected since their very first use. However, even with mass market devices, such as, smartphones, keyboards, or other wearable devices, time and training is required to achieve a minimum degree of training. If people who are sighted were to avoid using a new smartphone because the autocorrect function fails in completing their messages, smartphones would not be among the most disruptive devices. Also, training is needed in new technology. To this end, individual's milieu (i.e., family, assistants, organizations) have the responsibility to support individuals in their adoption process, rather than discarding technology if they do not work as expected the first time and they create frustration.

5 Market Factors

The design of any technology has to take into consideration both the technical and the human factors. However, this is even more important in the development of assistive technology, and specifically, in the context of people with multisensory impairments, because there are several barriers to including the final user in the design process, such as, the limited number of users who will benefit from technology, and the fragmentation of this niche market into smaller groups.

5.1 Bi-directional Communication is Crucial

There is an urge for additional research on enabling output in touch-based communication. In this regard, recognition and representation of touch work in a completely opposite fashion with respect to other senses, such as, vision, and hearing. In this context, output devices are increasingly effective and performing in representing images, videos, and audio in very high definition. Although they are still far from the human eye or ear, screens and speakers have dramatically been improving their quality and reducing their size, in the last decade. In contrast, image and speech acquisition techniques evolved at a slower pace, and their performance increased in the last few years, only. As a result, output devices have a longer history and are more effective compared to input devices. Conversely, there is a large gap between input and output in touch-based devices. Specifically, very little has been done on eliciting tactile cues, compared to the body of research and commercial work on input devices.

5.2 Glove-Based Devices Can Be Different Than Gloves

Several research projects about enabling touch- and gesture-based communication for people with sensory and multi-sensory impairments resulted in the development of glove-like devices. Unfortunately, several factors make them unsuitable for production and for adoption by their target users. Indeed, mechanical stress on electronic components and stretching of parts including connectors, and flexing areas in which soldering renders the majority of devices which are conceived as a glove unpractical. In contrast, the results studies from other fields about non-conventional interfaces and their social acceptance led to the design of interesting concepts which have better appeal and durability. Similarly, other structures and shapes could accommodate for sensors and actuators, and simultaneously provide higher durability, social acceptance, and easier access to the production phase.

5.3 Organizations as Gate-Openers

Organizations have a key role in fostering research on the introduction of new technology as can be a facilitator or an entry barrier to innovation: with respect to the former, several of them do an excellent work with technology leaders. However, less is being done to support novel devices, because sometimes the need of preventing frustration from the adoption of the wrong technology affects the development of new, effective devices.

6 Conclusion

People who suffer from sensory, or multi-sensory conditions, such as, deafness or deaf-blindness, respectively, rely on sensory substitution to be able to communicate and interact with the world. This includes using languages based on the conversion of words into gestures (e.g., the American Sign Language), in presence of damage to the sense of hearing. On the contrary, blind and deaf-blind people use touch as their primary communication channel for reading and writing, and even for any types of communication need.

In this paper, we specifically focused on touch-based alphabets and communication tools which are currently available to people with sensory or multi-sensory impairments. Specifically, the purpose of our work was evaluating the characteristic which lead to viable glove-based devices for end users. To this end, in addition to describing the features of languages based on touch, we introduced a new approach to the design and development of assistive technology. Specifically, we categorize the majority of tactile languages as based on three types of actions, that is, gesture, pressure, and touch. This, enables further classification based on other dimensions, such as, the space in which they occur, the type of tactile component which they include, the type of sensitivity required, and other components. Also, future work will include the dynamic component of tactile alphabets, that is, movement, and will focus on how it affects the static aspects. Nevertheless, the proposed classification enables to standardize and simplify the understanding and the implementation of both the hardware and the software components of assistive systems.

Furthermore, we described how the four main components of tactile alphabets can be implemented in wearable devices for supporting communication and interaction. Hence, we identified several best practices from the literature and we proposed new evaluation criteria in the selection and in the use of hardware. In this regard, as several design patterns emerge from the scientific literature and from commercial devices, we foster the creation and the adoption of a standard, in order to reduce risk of developing prototypes which increase fragmentation in the scenario of assistive technology without providing any benefit to the final users.

In our discussion, we highlighted several issues, including the lack of output devices and the consequent need for haptic interface which support bi-directional communication. This is particularly important as input-only systems create a barrier to the adoption of technology for touch-based communication, as the user will have to switch between two different interaction systems.

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