Ramiro VELAZQUEZ, Omar BAZAN, Jorge VARONA

Mechatronics and Control Systems Lab., Panamericana University

Wearable Electronic Tactile Display for the Foot

Abstract*. This paper presents a novel wearable interface for the foot: a shoe-integrated tactile display that enables users to obtain information through the sense of touch of their feet. A four-point array of actuators stimulates the mechanoreceptors in the foot sole with vibrations. A series of perceptual experiments involving directional information, pattern and emotion recognition, and language learning were conducted with 20 voluntary subjects. Results obtained show the potentials of podotactile stimulation and the proposed device.*

Streszczenie. *W artykule przedstawiono rozwiązanie dla wyświetlacza dotykowego montowanego w bucie. W ten sposób tworzony jest interfejs, który obsługiwany jest stopą użytkownika. Zamontowane w czterech punktach siłowniki stymulują mechanoreceptory w podeszwie poprzez wibracje. Przeprowadzono badania eksperymentalne z pomocą 20 ochotników, które potwierdziły wysoki potencjał tego rodzaju interfejsu i proponowanego rozwiązania. (****Elektroniczny wyświetlacz dotykowy dla stopy****).*

Keywords: podotactile stimulation, vibrotactile display, tactile perception, wearable device.
Słowa kluczowe: stymulacja stopą, wyświetlacz dotykowy naciskowy, postrzeganie dotykowe, urządzenia zdatne do noszenia.

Introduction

Just as sight and hearing, touch represents a means of interaction and communication for human beings. Among other capabilities, touch provides a whole non-verbal language that can be developed and offer much more possibilities than it is traditionally believed.

Much of what is found in the literature about tactile communication concerns tactile stimulation of the fingers and hands. However, as the area of tactile feedback is a “hot” research topic especially in assistive robotics and complex multitasking environments, other body areas have been explored as well: wrist/forearm [1], abdomen [2], chest [3], tongue [4], ears [5], and head [6] have been studied to transmit information to a user (a comprehensive survey of wearable tactile devices can be found in [7]). Devices are as diverse as the technology used and the location on the body. Yet, the human foot has not received much attention.

Tactile paving or tactile ground indicators are with no doubt the most representative example of tactile communication with the feet. They consist of regularly textured ground areas in the form of patterns of raised domes or bars. Their purpose is to provide a tactile surface that can be felt underfoot and recognized by pedestrians either as hazards in the immediate location (dome pattern) or as a safe direction of travel (bar pattern). They are widely used in stairways, ramps, escalators, road crossings, subway/railway platforms, etc.

Tactile ground indicators are of great help for both distracted sighted and blind pedestrians. However, their main inconvenient is that they just cannot be installed everywhere. A wearable electronic tactile-foot (podotactile) stimulation device could be interesting for providing diverse real-time information such as directions, situation awareness, alert signals, etc.

During the last years, we have being exploring the feasibility of providing tactile feedback via the feet. We have previously proposed in [8], a wearable human-computer interface for the foot consisting of a shoe-integrated vibrotactile display. This device was a first attempt to evaluate the role of tactile perception by the human foot. Perceptual experiments conducted with both sighted and blind users [8], [9] suggest that the comprehension level achieved is sufficient to be exploited in human-computer interaction tasks such as virtual reality, robotics, sensory substitution, game and entertainment, among many others.

Following the lessons learned from the first device, we report our progresses in podotactile stimulation with a technologically improved second device. This paper presents first a technical overview of the second prototype developed and then evaluates the capabilities of podotactile stimulation through a set of perceptual experiments performed on a group of 20 voluntary subjects. Results provide interesting insights into the real potential of podotactile perception and confirm the applicability of this approach in human-computer interaction.

Design and prototype

The conceptual representation of the second version of shoe-integrated tactile display is shown in Fig. 1(a). This design consists of four vibrating motors that stimulate the medial and lateral plantar areas of the foot sole, which are the most sensitive to vibrotactile stimulation [10].

In this prototype, vibrators are arranged in a diamond-like shape with 35 mm side-length (Fig. 1(b)). All four actuators are integrated in a commercial inexpensive foam shoe-insole. They provide axial forces up to 13 mN and vibrating frequencies between 10-55 Hz. Each vibrator is independently controlled with a specific vibrating frequency command.

This device is completely wearable and is intended to be used on the left foot (Fig. 1(c)): it includes an RF (radiofrequency) transmission module which allows simple and reliable point-to-point communication with a computer within a range of 100 m. It also includes the electronic drive to power the vibrating motors and an on-board power supply that ensures 6 h of autonomy. Fig. 1(c) inset details the electronic module that the user carries comfortably attached to the ankle. The prototype’s laboratory cost is low (only 200 USD) and it is easy/fast to assemble and maintain.

A key aspect of this prototype is a simple but effective mechanical design for ensuring an optimal transmission of vibrations to the skin. Foam insoles were chosen because foam is easy to machine and it is well known for absorbing vibrations, shock, and impact forces. Its absorbing material properties have a twofold purpose: to cushion the motors against the user’s load and to prevent from having an expanding vibration effect throughout the insole. Dots of an epoxy paste cover the motors’ entire upper surface and are in contact with the foot sole.

However, embedding the actuators within foam implies that vibrations transmitted to the skin will be damped as well. A simple solution to overcome this undesired attenuation is to set the motors at 45°. Fig. 2 illustrates this concept. When motors are perfectly set on the foam, an entire side of their structure is evidently in contact with the foam. In consequence, vibrations find a large viscoelastic contact surface that damps significantly their amplitude.

When motors are set at 45°, an entire side of the motor is contact-free. This produces vibrations of greater amplitude that are only transmitted to the solid epoxy paste. This simple design has experimentally proved to be an excellent vibration transmitter.

Evaluation and Results

Perceptual experiments were carried out to evaluate the prototype's ability to transmit tactile information to the user and to gain insights into the capabilities of podotactile perception. Four experiments were conducted for this purpose: direction, pattern, emotion recognition, and language learning.

A total of 20 subjects (14 men and 6 women) participated voluntarily in the experiments. All gave their consent in agreement with the university ethics guidelines. Subjects were undergraduate students at Panamericana University with no known impairments in tactile sensory or cognitive functions. Their ages ranged from 19 to 23 years old with an average age of 20.4. None of them reported previous experience using tactile displays.

During the experiments, the subjects were wearing the tactile display on the left foot. For hygiene, all subjects were requested to use socks. Before each session, they were totally naive about all aspects of the test and were given general instructions concerning the task. A short familiarization time was granted prior to the tests. During this time, the subjects tested different vibration frequencies and had the opportunity to choose a preferred one. All 20 subjects chose 55 Hz, the maximum vibration frequency of the actuators. For all subjects, the ensemble of experiments was conducted consecutively on the same day.

For statistical analysis, subjects were divided into two groups of 10 according to their educational background: engineering and non-engineering students. The first group involved subjects enrolled in Electronics Engineering and Computer Science while the second, subjects enrolled in programs such as Business Administration and Liberal Arts. The χ^2 distribution was used to evaluate difference in proportions across samples of a same group while the z-test to give a confidence interval for the true difference in proportions between groups. The level of significance to reject the null hypothesis (α) was set to 0.05 in all cases.

A. Cardinal direction recognition

The purpose of this test was to determine whether the subjects could recognize directional information represented by the cardinal points.

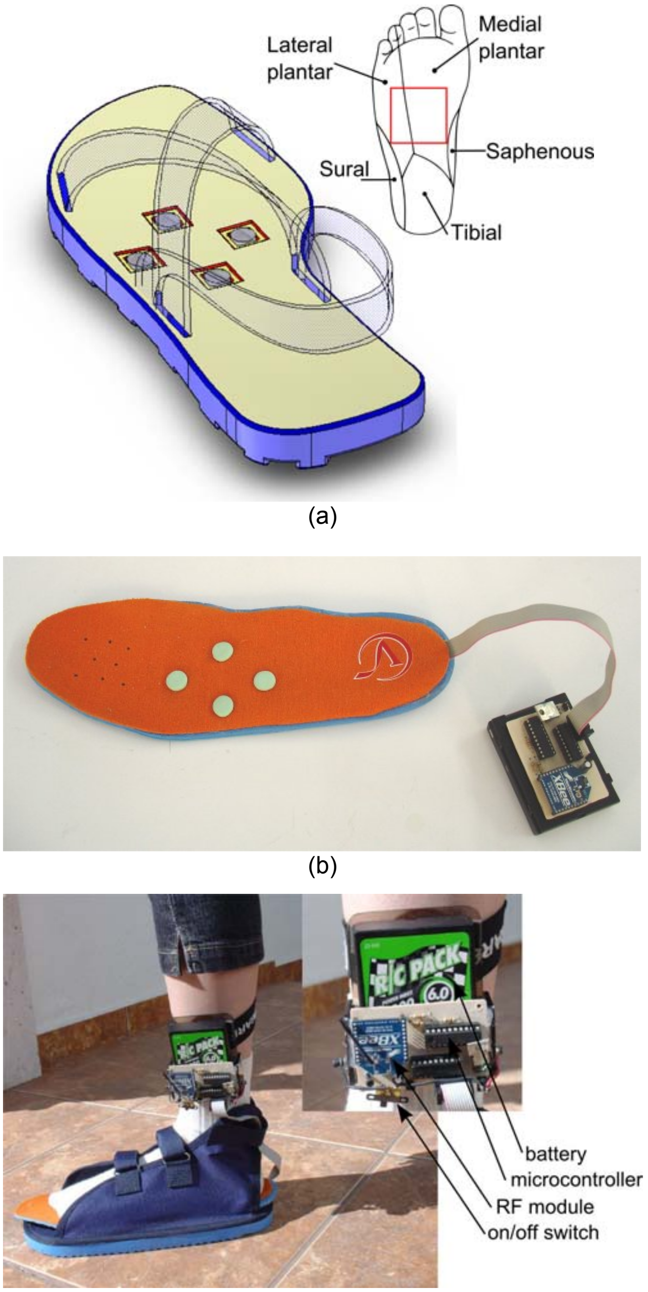
Method:

Each one of the four contact pins of the tactile display was set to represent a cardinal point. A cardinal direction is encoded in five sequences (t1-t5) as follows: three consecutive short vibrations in the corresponding contact pin, then a short vibration in the opposite contact pin, and again a short vibration in the correct contact pin.

Fig. 3 shows for example, the codification for North. Note that the contact pin **N** vibrates three times, then **S** once, and again **N**. A set of 14 directions was presented to the subjects in one trial. All 20 subjects were asked to report the direction perceived with no time restriction. Upon request, they could have the direction pattern refreshed on the display.

Results:

Results obtained are presented in confusion matrices (Table 1). For the engineering group, the average recognition rates were 83.3%, 90%, 87.5%, and 96.6% for **N**, **S**, **E**, and **W**, respectively. For the non-engineering group, these were 100%, 92.5%, 70%, and 86.6%, respectively. Note an overall good performance.



(a)

(b)

(c)

Fig.1. Tactile display for the left foot: (a) Design concept. Inset: target stimulation area enclosed in square. (b) Prototype. (c) Fully wearable device with wireless connection. Inset: electronic module. Design concept and prototype were acknowledged US Patent Application 20110242316 [11].

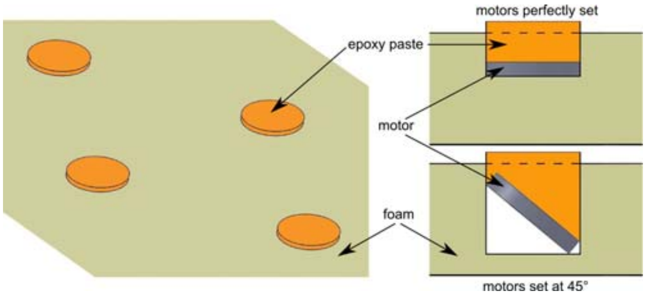


Fig.2. Arrangement of vibrating motors within the foam. When motors are set at 45°, vibrations of higher amplitude are transmitted to the foot sole.

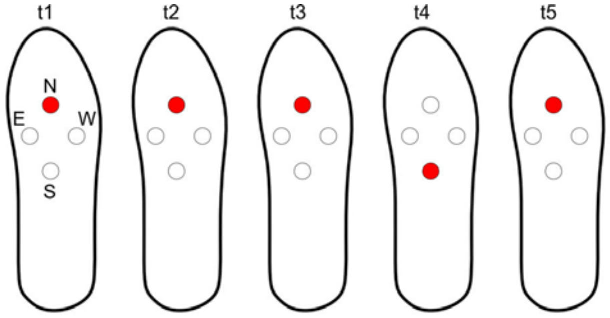


Fig.3: Schedule of activation of the motors for the cardinal direction recognition task (example for North).

Table 1. Cardinal direction recognition: average confusion matrices for the Engineering and Non-Engineering groups.

Eng.		answered (%)			
		North	South	East	West
presented	North	83.3	3.33	10	3.33
	South	2.5	90	2.5	5
	East	0	10	87.5	2.5
	West	0	3.33	0	96.6

Non-Eng.		answered (%)			
		North	South	East	West
presented	North	100	0	0	0
	South	7.5	92.5	0	0
	East	17.5	7.5	70	5
	West	0	10	3.33	86.6

Subjects in the engineering group exhibited a uniform performance across the test (χ^2=2.97, p=0.39). However subjects in the non-engineering group did not (χ^2=15.17, p=0.0016). For this group, East and West were significantly more difficult to identify than North and South. There was no statistically significant difference in the recognition rates between groups for South and West (p>0.05). Not so for North and East (p<0.05).

B. Pattern recognition

In human-computer interaction, there is much interest in coded language: non-verbal visual, audio, or tactile structured short messages that can provide information to the user. This test aimed to determine whether the subjects could recognize and associate tactile patterns displayed on the foot with familiar signals.

Method:

Five tactile patterns were used for this test: caution, SMS, phone call, tic-tac, and door knocking melody. Vibrotactile signals were modulated in accordance to these patterns:

- Caution was inspired by its visual equivalent: two intermittent vertical bars (highway signal). This pattern was generated by the alternative activation of pins **E-S** and **N-W** (refer to Fig. 3 for pin identification).
- SMS was generated in accordance to mobile phones: two consecutive short vibrations, then a pause, then two consecutive short vibrations. All four pins vibrated simultaneously when required.
- Phone call was also generated as in mobile phones: a long vibration, then a pause, then a long vibration. Again, all four pins were involved in this pattern.
- Tic-Tac intended to simulate the sound of a ticking clock. This pattern was generated by activating pin **E**, then a short pause, then pin **W**.
- Door knocking melody intended to reproduce the well-known melody used when knocking on a door or when honking: five consecutive short vibrations, then a pause, then two consecutive short vibrations. Pins **N** and **S** were involved during the first five vibrations while all pins for the last two.

All 20 subjects were asked to match what they felt tactually with one of these patterns. The test consisted of a single trial. No familiarization time with the patterns was granted prior to this test. Each pattern was displayed once. Subjects had no time restriction to provide their answers. Upon request, they could have the pattern refreshed on the display and they were allowed to modify their answers if they felt one pattern suited better an answer already given.

Results:

Table 2 summarizes the results obtained for both test groups. For most of the patterns, engineering students (Eng.) obtained higher average success rates than non-engineering students (Non-Eng.). However, there was no statistically significant difference in the performances of the two groups (p>0.05). Subjects in both groups exhibited a uniform performance across the test (Eng. Group: χ^2=8.67, p=0.06, Non-Eng. group: χ^2=2.88, p=0.57).

Note that the SMS, phone call, and melody patterns were quite well identified by most of the subjects while tic-tac was sometimes confused with caution and SMS.

These results suggest that people can easily identify and relate tactile-foot patterns to familiar visual, audio, or tactile signals.

Table 2. Pattern recognition: average confusion matrices for the Engineering and Non-Engineering groups.

Eng.		answered (%)				
		Caution	SMS	Call	Tic-Tac	Melody
presented	Caution	80	10	0	10	0
	SMS	0	70	0	30	0
	Call	0	0	100	0	0
	Tic-Tac	20	20	0	60	0
	Melody	0	0	0	0	100

Non-Eng.		answered (%)				
		Caution	SMS	Call	Tic-Tac	Melody
presented	Caution	50	10	20	0	20
	SMS	10	50	0	40	0
	Call	10	20	70	0	0
	Tic-Tac	20	20	0	60	0
	Melody	20	0	0	0	80

C. Emotion recognition

Emotions are necessary for us humans to function properly. Research has shown that they play an important role in our decision making mechanism and imbue strong or important events in our memory [12]. For example, we might remember losing money by associating the event to a negative emotion, whereas the birth of our child to a positive emotion.

Because of the aforementioned, digital treatment of emotions has been an active area. In particular, research has been carried out to generate, display, and recognize emotions. While this work does not pretend to present an emotional architecture, like the ones discussed in [13]; it does notice that emotions can be displayed by conventional and nonconventional means. Examples of the first are facial and verbal expressions while a representative example of the second is the work reported in [14], where a virtual flock displays emotions through its movement.

It is recognized that music is a conventional mean of inducing strong emotions. Cinema musical scores are particularly effective at transmitting emotions to the audience. Moreover, the audience can actually perceive and remember emotions transmitted by music [15]. Perhaps the clearest example is the musical score of the movie Jaws, which effectively transmits the emotion of fear.

Method:

The emotions selected for the third test are a subset of the so-called primary emotions: happiness, sadness, anger, and fear. To transmit this emotional content, vibrations similar to those produced by sound were modulated in the shoe-integrated tactile display according to these patterns:

- Happiness was inspired by laughter. It is the most evident visual expression of happiness. This emotion was generated by a set of three strong short vibrations, then a pause, and again three strong short vibrations. This pattern intends to reproduce the iconic "Hahaha!".
- Sadness is characterized by feelings of disadvantage such as sorrow and lowering of mood. This emotion was generated by setting all four vibrators at maximum vibrating frequency and gradually decreasing their frequency until vibration is no longer perceived. This pattern intends to communicate a lowering of energy.
- Anger can be defined as an emotional response to a perceived provocation. This emotion was generated by setting all actuators at a low -yet perceivable- vibrating frequency and suddenly setting them all at maximum frequency. This pattern intends to communicate an explosion of feelings.
- Fear is a distressing emotion induced by a perceived threat. To generate this emotion, we coded the classical musical score of the movie Jaws.

Subjects were asked to match what they felt tactually with one of these emotions. The test consisted of a single trial. No familiarization time was granted prior to this test. Each emotion was displayed once. Subjects had no time restriction to provide their answers. Upon request, they could have the emotion refreshed on the display and they were allowed to modify their answers if they felt one emotion suited better an answer already given.

Results:

Table 3 summarizes the results obtained for the 20 subjects. Again, for all emotions, engineering students (Eng.) obtained higher average success rates than non-engineering students (Non-Eng.). However, this is not enough to state that there was a statistically significant difference in the performances of the two groups (p>0.05). Subjects in both groups exhibited a uniform performance across the test (Eng. group: χ^2=0.43, p=0.93, Non-Eng. group: χ^2=1.66, p=0.64).

Table 3. Emotion recognition: average confusion matrices for the Engineering and Non-Engineering groups.

Eng.		answered (%)			
		Happiness	Sadness	Anger	Fear
presented	Happiness	70	0	20	10
	Sadness	0	80	0	20
	Anger	20	0	80	0
	Fear	10	10	0	80

Non-Eng.		answered (%)			
		Happiness	Sadness	Anger	Fear
presented	Happiness	50	20	30	0
	Sadness	0	70	10	20
	Anger	50	0	50	0
	Fear	10	10	10	70

Note that the proposed tactile emotions were easy to recognize by most of the subjects. It is interesting to note that anger was sometimes confused with happiness. For some subjects, the explosion of feelings sensation can also be interpreted as happiness. Note that the Jaws musical score obtained high recognition rates. Subjects were asked at the end of the test if they had recognized the melody. None of them did and realized when told. This confirms how well the melody represents fear.

Results obtained from this test strongly suggest that people can easily relate vibrotactile-foot patterns to emotions.

D. Language learning

Language learning is the process by which humans acquire the capacity to perceive and use words to understand and communicate [16]. From a neuroscience point of view, the language learning process is very different whether it is the first or second language. While the first refers to an infant's acquisition of his native language, the second deals with the process of learning an additional language when a native one has been already learned.

In particular, learning a second language is a complex process extensively studied in neuroscience, applied linguistics, sociolinguistics, psychology, and education. With no intention of further reviewing this process, we shall limit the discussion to state that humans learn a second language by making relations with their own native language and by memorizing. Think of a Spanish speaking native learning Italian; as both are Latin-based languages, relations can be easily established. However, for a Spanish speaking native learning Chinese, memorizing words seems the only way.

In this context, we propose a fourth test dealing with memorizing and tactile language learning. Its purpose is to evaluate whether the subjects could quickly learn tactile words and retain them in memory.

Method:

Five tactile words were chosen for this test: day, night, water, hello, and goodbye. The vibrotactile patterns in Fig. 4 were arbitrarily chosen to represent these words. For example, "day" in tactile language is represented by a long vibration followed by a short one while "night" by a long vibration followed by a short one, and again a long vibration.

Subjects were asked to match what they felt tactually with one of these words. Before each session, all five tactile words were displayed to the subjects so that they could make a mental representation of them. Upon request, they could have the tactile word refreshed on the display. When ready, the tester made a 1 min small talk on purpose to distract their mind from the test. After that, the test started. It consisted of a single trial. Each word was randomly displayed twice. Subjects had no time restriction to provide their answers and they were allowed to modify them if they felt they had made a mistake.

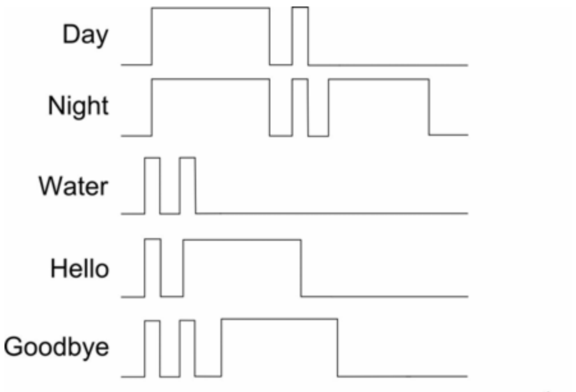


Fig.4: The five tactile words.

Results:

Table 4 shows the results obtained from this session. Note that the Eng. group obtained once again higher average success rates. For this test, the Eng. group was statistically significant better than the Non-Eng. group particularly at recognizing the “night” and “goodbye” patterns ($p<0.05$). Subjects in the Eng. group did not perform uniformly across the test ($\chi^2=18.21$, $p=0.001$). For this group, “day” and “hello” were significantly more difficult to identify than the other three tactile words. On the other hand, the Non-Eng. group performed uniformly across the entire test ($\chi^2=7.47$, $p=0.11$).

Table 4. Language learning: average confusion matrices for the Engineering and Non-Engineering groups.

Eng.		answered (%)				
		Day	Night	Water	Hello	Goodbye
presented	Day	75	15	0	10	0
	Night	0	100	0	0	0
	Water	0	0	95	5	0
	Hello	25	0	0	65	10
	Goodbye	0	0	0	0	100

Non-Eng.		answered (%)				
		Day	Night	Water	Hello	Goodbye
presented	Day	75	10	0	10	5
	Night	5	55	0	5	35
	Water	0	0	80	10	10
	Hello	20	15	0	55	10
	Goodbye	5	15	15	20	45

When asked about the effort invested, all subjects stated that this last test was the most difficult and that it required high concentration.

Results obtained from this test are undoubtedly encouraging: they strongly suggest that people can easily understand, learn, and remember abstract vibrotactile-foot patterns and relate them to verbal language.

Conclusion and future work

This paper has presented the design, technical overview, and preliminary evaluation of a shoe-integrated tactile display.

Using vibrating motors, a simple, fully wearable, low cost, and easy/fast to assemble device has been proposed to stimulate the mechanoreceptors in the foot sole.

Some insights into the role of tactile perception by the human foot were evaluated through a set of tests involving direction, pattern and emotion recognition, and language learning. Results obtained from these tests seem very promising for podotactile stimulation.

Success rates in cardinal direction recognition strongly suggest the possibility of guiding people through environments. This could be exploited in virtual reality or in mobility assistive devices for the blind. We found that vibrating patterns indicating cardinal directional information are easier to understand if the opposite direction is also displayed to indicate a direction. This provides a reliable reference to identify points of vibration when users are unable to locate them precisely throughout the foot sole.

Familiar patterns and emotions can be easily recognized by the foot if information displayed is simple and encoded as short structured messages. This could be useful for applications using alert signals and platforms communicating emotions (such as games and platforms seeking to complete visual feedback with haptics).

New patterns abstractly representing verbal language can also be understood, quickly learned, and retained in memory.

Tactile-foot feedback seems slightly easier to understand for those with engineering background. This is certainly due to the spatial-temporal reasoning skills developed during education that allow an easier visualization and conceptualization of abstract and spatial concepts.

Future work will focus on language learning: several tactile words will be displayed sequentially expecting that subjects are capable of constructing sentences. This intends to broaden the possibilities for describing complex ideas and situations.

REFERENCES

[1] G. Ng, P. Barralon, G. Dumont, SK. Schwarz, and JM. Ansermino, Optimizing the tactile display of physiological information: vibro-tactile vs. electro-tactile stimulation, and forearm or wrist location, *Proc. of Annual Int. Conf. of the IEEE Engineering in Medicine and Biology Society* (2007), 4202-4205.

[2] K. Tsukada and M. Yasumrua, ActiveBelt: belt-type wearable tactile display for directional navigation, *Proc. of UbiComp* (2004), Springer LNCS 3205, 384-399.

[3] L. Jones, B. Lockyer, and E. Piateski, Tactile display and vibrotactile pattern recognition on the torso, *Advanced Robotics*, 20 (2006), 1359-1374.

[4] E. Sampaio, S. Maris, and P. Bach-y-Rita, Brain plasticity: visual acuity of blind persons via the tongue, *Brain Research*, 908 (2001), 204-207.

[5] F. Gemperle, N. Ota, and D. Siewiorek, Design of a wearable tactile display, *Proc. of Int. Symp. on Wearable Computers* (2001), 5-12.

[6] J. Kalb, B. Amrein, and K. Myles, Instrumentation and tactor considerations for a head-mounted tactile display, Technical Report ARL-MR-705 (2008).

[7] R. Velazquez, Wearable assistive devices for the blind. In A. Lay-Ekuakille, S.C. Mukhopadhyay (eds.), *Wearable and autonomous biomedical devices and systems* (2010), Springer LNEE 75, 331-349.

[8] R. Velazquez, O. Bazan, M. Magaña, A shoe-integrated tactile display for directional navigation, *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems* (2009), 1235-1240.

[9] R. Velazquez and O. Bazan, Preliminary evaluation of podotactile feedback in sighted and blind users, *Proc. of Annual Int. Conf. of the IEEE Engineering in Medicine and Biology Society* (2010), 2103-2106.

[10] P. Kennedy and T. Inglis, Distribution and behavior of glabrous cutaneous receptors in the foot sole, *J. Physiol.*, 538 (2002) No. 3, 995-1002.

[11] R. Velazquez, Shoe-integrated tactile display for directional navigation, US patent application filed on Sept 23, 2010, US Patent Application 20110242316 published on Oct 6, 2011.

[12] J. LeDoux, Emotion circuits of the brain, *Annual Review of Neuroscience*, 23 (2000), 155-184.

[13] C. Delgado-Mata, Emotion signalling in multiple intelligent virtual agents for believable artificial animals, *PhD thesis* (2004), University of Salford.

[14] J. Ibañez, Showing emotions through movement and symmetry, *Computers in Human Behavior*, 27 (2011), 561-567.

[15] S. Eschrich, T. Munte, and E. Altenmuller, Unforgettable film music: the role of emotion in episodic long-term memory for music, *BMC Neuroscience*, 9 (2008), No. 48.

[16] M. Tomasello, Origins of human communication (2008), MIT Press.

***Authors**: Dr. Ramiro Velazquez, E-mail: rvelazquez@up.edu.mx; Omar Bazan, Email: israel.bazan@up.edu.mx; Dr. Jorge Varona, E-mail: jvarona@up.edu.mx Mechatronics and Control Systems Lab., Panamericana University, Fracc. Rústicos Calpulli CP 20290, Aguascalientes, Mexico.*