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An Electrical Stimulator for Sensory Substitution

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Abstract—**This work presents an electrical stimulator system for use in sensory substitution (SS), as a mobility aid for visually handicapped people. The whole system passes visual information via cutaneous stimulation, and consists of a webcam, a PC, dedicated hardware to generate stimuli and a 15x20 electrode matrix. The same system can also be used in psycophysical and somesthesic research, or even for SS of deaf people, by changing the input signal from a camera to a microphone, and adapting its control software. Circuits for pixel addressing, for signal generation and for switching are described, as well as the software involved in generating a pulse train, which configures the stimuli patterns.**

I. INTRODUCTION

Sensory Substitution (SS) is something well known and has been used for quite some time, specially when blind people read in Braille, using touch to replace vision, or deaf people do lip reading, using vision to replace hearing. In both cases training is necessary, because contrary to popular beliefs, the lack of one sense does not automatically improve the remaining ones. [4]

To allow visual information to be received through touch, a system was developed at LAC (Laboratory of Automation and Control) of EPUSP (Escola Politécnica da Universidade de Sao Paulo), consisting of dedicated hardware and software. The intention is not to completely create artificial vision, because its resolution and frame rate are far lower than natural human vision. However, its limitations are suitable for helping visually impaired people in assembling mental images of their surroundings, as well as reading of doors, buildings and bus signs, when the blind need help from others. This permits quicker information gathering than traditional orientation and mobility (OM) techniques, which consist basically of searching algorithms of the surroundings, usually taking too long [1].

This system "draws" in the user's skin a simplified version of a picture taken from the surroundings or from written signs [39], [40]. The first prototype was composed of a webcam, PC, microcontroller, stimulation hardware and electrode matrix. The final prototype replaced the webcam and PC by a MOS image sensor interfaced directly to the processor board, as shown in figure 1. The webcam captures an image, which is then digitally treated at the PC to detect its edges, lower its details and resolution, binarize it, transforming it from an image of 240x320 colored pixels to 15x20 binary pixels, i.e., just 300 bits.

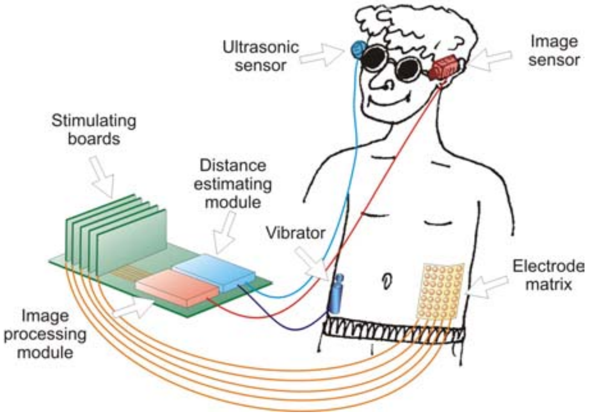

Fig. 1. General view

These 300 bits are then passed serially to a dedicated hardware that sends electrical stimuli to an electrode matrix on the user's abdomen, activating each electrode corresponding to each lit pixel in the image.

Also, to compensate for the lack of stereoscopy from using just one camera, an ultrasonic sensor is used to estimate the distance to an obstacle and activate an eccentric motor, similar to cell phone vibrators. This way, the closer the object, the more the motor vibrates, so the user can differentiate from a large and distant object from a smaller and closer one.

This system was inspired from works initiated in 1993 by [13], but now much deeper and adding techniques to focus in the solution of specific problems. One example is the image pre-processing to compensate for the touch limitations when compared to vision, which has layers of nerve cells dedicated to detect edges. Besides, touch has a much lower density of receptors and a lower cortical representation than vision [2], [3].

The edge detection and resolution reduction is done using filter algorithms like Sobel, Canny and others, [18], [19], and to simplify the image non-linear techniques like scale space and anisotropic diffusion are used [20], [21], [22].

A. *Other researches*

Using SS there are other works dating back to the 70's, and the technology is still under development [5], [6]. There

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are several groups in the world trying to improve the life of visually handicapped people, developing basic research and SS equipments [7], [8], [11], [14], [15], [25], [26], [27], [28] [29], [30], [31], [32], [37], developing visual prosthesis towards a artificial retina [8], [9], or even trying to directly stimulate the cerebral cortex [10]. There are also groups studying SS for artificial proprioception for use in prosthesis, in virtual reality and teleoperation, and even as additional information channel for fighter jet pilots [12], [13], [14], [15], [16], [17], [33], [36].

However, it is important to point out that this system does not intend to completely recover vision like other long-term researches try, it tries to improve life condition in a shorter time, by solving practical daily problems.

II. HARDWARE

From the beginning a main concern was to create a portable low cost system, as flexible as possible, to make it accessible to most people, both handicapped and researchers with low budgets. Two prototypes were developed, the first with lower resolution, only 5x7, to prove some concepts, and a more optimized, larger one, with 15x20 pixels. Some electrode matrices were developed, two of 5x7 but with smaller and larger electrodes, closer or more apart, following principles found in [7], [12], [17], [24] and [38]. The final 15x20 prototype was made in flexible material, of silver chloride ink over a polyamide film.

Its test and training was done in three stages:

- Adjustment of the best parameters, choice of smaller closer electrodes, and method of stimulation;
- Training of simple geometric patterns;
- Tests with simple controlled images.

The first two could be done without the camera, using only the microcontrolled stimulator.

A. *Overview*

The equipment circuits are formed by column boards and a motherboard, which receives the signals and distribute amongst the column boards. These boards have several different functions:

- A digital part to address and hold the control word for each column;
- A timer to create the oscillation (later disabled when receiving the signal from the 8052);
- Amplification of the oscillation signal;
- High voltage (between 50 and 100 Volts) switching elements, one for each pixel;
- LEDs that allow the researcher to know what pattern is being sent to user, useful during the training period.

These boards form a bus, and the LEDs on the top form the same image that is being processed, but can be turned off by one jumper. In the final version these are not needed, and they can be cut off to save batteries. Also, a switch will be added in the final version to allow capturing the image only when needed, saving batteries.

Voltage stimulation is used instead of current stimulation, to insure that if the electrode matrix detaches from the skin, the coupling resistance increases and the power delivered to the skin falls. It could fall below the skin sensibility threshold and the user stop feeling the sensation, but at least the user does not get injured. This is more probable to occur due to the large size of the matrix, approximately a letter size page, making it more difficult to have a perfect connection with the skin all over the matrix.

The equipment is shown on figure 2, with five stimulation boards, one for each column, to drive a 5x7 array. The design allows for up to 15 boards in the motherboard, implemented in the second prototype, whose CPU, power supply and the new stimulation boards are in figure 3.

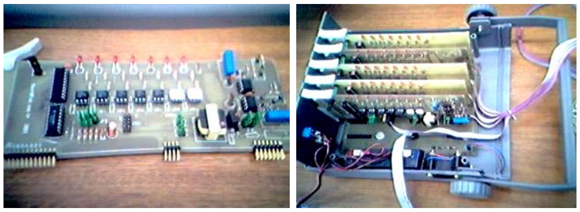

Fig.2. The first prototype with 5 stimulation boards, one for each column

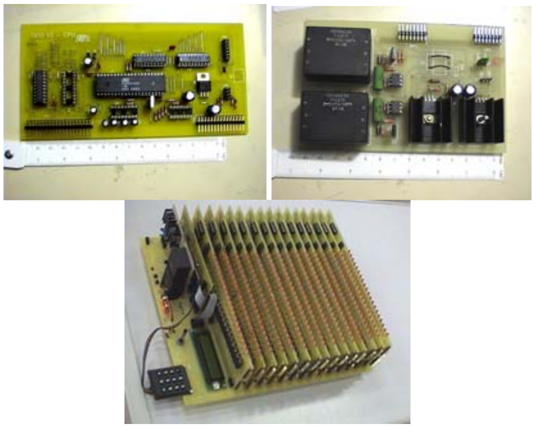

Fig. 3. CPU, power supply and stimulation boards of the second prototype

B. *Sitmuli generation*

The type o stimuli generally used in motor and sensorial stimulation is a pulse train, which can be monophasic or biphasic, i.e., have DC level non-zero or zero. There is a debate for which one is better, with most preferring biphasic signals to avoid ionization of the skin [12], [40], [41], [42].

The signal is generated with as burst of pulses, generated by two ways, the first option by hardware timers. Alternatively, by selecting a few jumpers, the boards receive the signal from a microcontroller output pin, whose oscillation is adjusted by software. In both we can adjust the quantity of pulsed per burst, the time high and low of each pulse, the interval between bursts.

To lower the power consumption, a dead time is inserted between a high and low pulse.

The pulse train shown in figure 4 is generated by a microcontroller line and amplified by a transistor on switch mode activating a pulse transformer, shown in figure 5.

C. . Pixel addressing

Figure 6 shows the address circuit for each stimulation board, using 4 lines from the microcontroller to compare to a local board address, enabling the latch to copy the seven microcontroller lines that bring the pixel values to activate the optocoupler on figure 7, enabling the amplified pulse to reach each activated electrode.

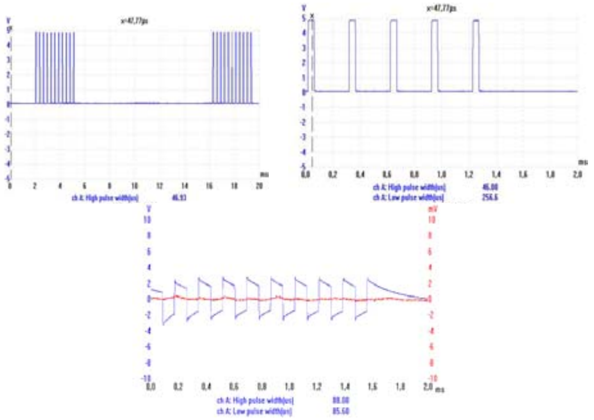

Fig.4. Electrical stimulus captured in digital scope PicoScope ADC-212, before and after the amplification stage – monophasic stimulus (non zero DC level)

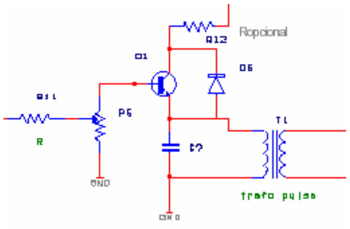

Fig.5. Amplification of the pulse train

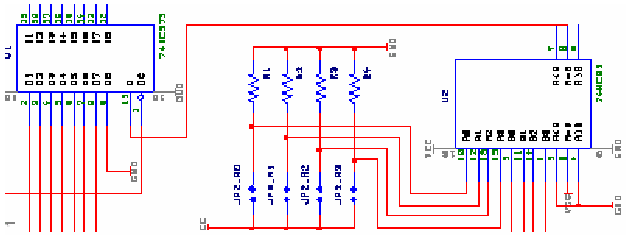

Fig.6. Address circuit on each stimulation board

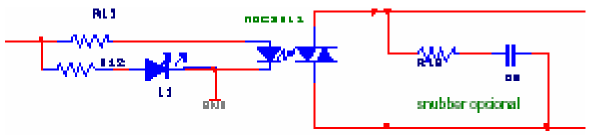

Fig.7. Switching circuit with SSR and optional snubber

Figure 7 shows the switching circuit. To insure the safety of the user, optocouplers of the solid state relays (SSR) type are used. They switch the higher voltage signal to the electrode array, allowing DC level tests with current flowing in both directions. In the second prototype, a transistor-type optocoupler plus a rectifier bridge was used, reducing the cost of each switch to one third of the SSR switches. Keep in mind that each equipment should have 300 hundred of them, so this represents the main cost.

In order to measure initial adjustments a board to simulate the skin impedance was used, by using a common model of the skin, with 10nF ceramic capacitor and a 1KΩ resistor in parallel, as seen on figure 8.

Another board was created, also seen on figure 8, to make easier current measurements for each electrode or for each board (all seven electrodes). It consists of an intermediate board, between the stimulation boards and the electrode matrix, with P1 female plugs that interrupt the circuit and insert a male P1 connected to a Fluke 87 true RMS multimeter was created. There is one plug for each electrode and for each column of the original matrix. The current measured was about 10 mA per electrode, with best sensation around 30 to 60 volts, depending on the user.

Fig.8. The RMS current measurement board and skin simulator board

III. SOFTWARE

In the PC, the image processing was done in Java but first prototyped in MatLab, using image processing and image acquisition toolboxes.

The microcontroller program was done in Hi-Tech C, except for some timer routines, done in assembler. This control program is responsible for the configuration of stimuli, by using just four keys. It uses an interface similar to wrist watches interfaces: two keys for up and down, one to accept the parameter value and one to go to the next parameter.

We choose the pulse parameters and then the geometric pattern to be trained. Finally, we choose the stimuli method, which can be similar to a stamp, with all columns simultaneous, by column keeping the previous ones, by column individually (turning off the previous ones) and pixel individually, sequentially, in the same manner a person draws with a pen.

In the tests, the correct recognition percentage is measured, as well as the time taken to recognize a pattern or image (latency).

IV. ADJUSTMENTS, TRAINING AND TESTING

The equipment is working and being tested. The tests consist of adjusting the waveform to the best sensation possible, then training the users with simple geometric patterns and later more complex simple geometric figures, and finally images of a controlled environment.

The subjects are divided into three groups, of normal sight, born blindness and acquired blindness. The first test consists of the adjustment of time high and low of each pulse of the burst, time between bursts, method of stimulation and size of electrodes and space between them. This determines the enveloping burst frequency and pulse train frequency, as well as their duty cycles. To test different electrode sizes two matrices were made, within the limits of recommendations found in the literature. We also tested both of the matrices, smaller and bigger, with better sensation using the smaller, which was then used for the remaining tests.

Another initial adjustment involved the method of stimulation, which could be chosen by software to act as a stamp, column by column or pixel by pixel. At the stamp, all electrodes of an image activated almost simultaneously, with just microseconds from one column to the next, which cannot be perceived by the user. Activating by columns, the time between each column is increased, with the option to keep the previous ones lit or not. Finally, on the pixel activation, only one electrode at a time is activated, and the patterns are “drawn” on the skin, simulating the same movement that a person would use to draw manually, in the same sequence. The adjustment tests showed that this last one, by pixel individually, resulted the best sensation and got the best recognition by the users, being the only one used from then on for the second phase of training and tests.

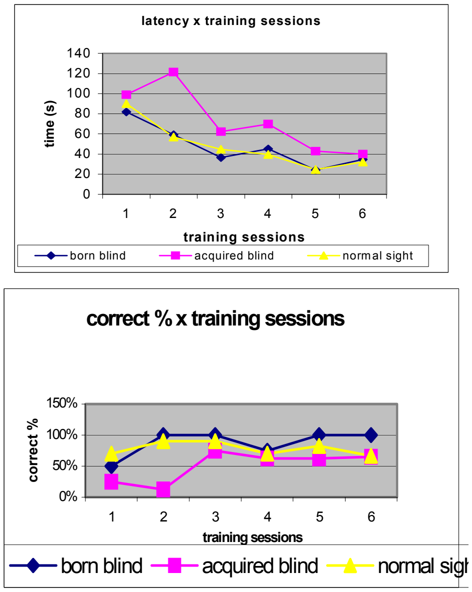

Figure 13. Preliminary results of the training sessions

The second phase trained the user with simple geometric patterns like straight lines in vertical, horizontal and inclined positions, and of simple geometric objects composed of the lines, like square, triangles pointing to the right and to the left, circle and a letter. Twelve training sessions of up to 40 minutes each were scheduled, but after six sessions the recognition of geometric patterns already improved, and the time to reach recognition (latency) fell, as illustrated on figure 13. The best results were among the group of congenital blinds, confirming similar results found on [6], [26], [31] and [35].

V. CONCLUSION

The system showed that substitution of vision using touch is feasible, and more testing is under way. The second prototype allows for larger images, although they are still small when compared to vision. However, as mentioned in the beginning, the idea is not to create artificial vision, the goal is to help blind people in assembling a mental map of unknown surroundings, which requires low resolution.

Adaptation of the brain is possible, according to Bach-Y-Rita and others. Calvert used FMRI (functional magnetic resonance imaging) to show that the same cortex region used by non-deaf people when listening were activated during lip-reading on deaf people [6], [31], [35], [34], [43]. The same could be proved to this system, we should check for signs of visual cortex activation when using the equipment, through EEG (electro-encephalo-gram) of at least 32 channels. FMRI uses magnetic fields and could not be used with this system.

Although the system was designed having a blindness problem in mind, it can be adapted to serve deaf people by changing the entry sensor from a webcam to a microphone.

Some recommendations found on the literature were used to the waveform characteristics, but the system is flexible enough to serve the purpose of experimenting with these recommendations on dealing with the somesthesic system by physiologists and experimental psychologists, and several researchers on the area showed interest in using it. Adjustments on the waveform can be made by software, while by hardware the amplitude is set via a multiturn potentiometer, and DC level (zero or not) can be chosen from a jumper.

A basic segmentation for sign recognition has been implemented [45], but will go through improvements in the future. At the moment we depend on the user to recognize letters and numbers in signs, using their own natural intelligence, but optical character recognition (OCR) could be used for recognizing them in the future, and either translate it to Braille and draw the Braille characters, or use voice synthesizers to speak them out.

Another improvements involve enhancements in the image processing algorithms, and in incorporating a switch to capture images only when needed, as if it were a photographic camera.

Another current study is to use digital signal processing (DSP) processors from Texas (TMS320C55) to allow for more computationally intensive algorithms, although the latency for recognizing one image being in the order of 30 seconds or more gives a large amount of processing time even when using 8052 compatible microcontrollers, existing some of more than 30 MIPS nowadays. Reconfigurable hardware (FPGAs) can also be used to further reduce the size of the entire system and are being evaluated.

Further improvement ideas can be found on [42] and [48].

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