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Enabling Students with Severe Disabilities to Communicate with Learning Environments

[1]M. Assaf*, [1]R. Kumar*, [1]K. Nambiar, [3]S. Narayan, [1]N. Nath, [2]Y. Reddy, [1]K. Sharma, [2]B. Sharma
[1]School of Engineering & Physics, Faculty of Science, Technology & Environment
[2]School of Computing Info & Maths, Faculty of Science, Technology & Environment
[3]Centre for Flexible Learning
The University of the South Pacific, Suva, Fiji
*Email: assaf_m@usp.ac.fj
*Email: kumar_ru@usp.ac.fj

***Abstract*—this paper presents the design of an assistive technology that allows people with disabilities to communicate with learning environments. We propose an assistive Tongue Drive System (TDS) which enables the end user to use their tongue to communicate by means of an Android Device. In this study, the design of the TDS is discussed.**

Keywords—Assistive technologies, Tongue-computer interface, Spinal cord injury, Brain Computer Interfaces, Magnetic field.

I. Introduction

We propose a new wearable wireless assistive technology allows students with disabilities to operate a computer without using the keyboard and mouse. The proposed technology enables students with severe disabilities to interact with and control their environments simply by moving their tongues. The Tongue Drive system could help individuals with severe disabilities lead more independent lives.

The main objectives of the proposed system are:

- To translate specific tongue gestures into computer commands.
- To sense the magnetic field created by a small generator applied to the student's tongue.
- To use wireless technology for communication of information between the magnetic field sensing device and computers, laptops, and tablets.

It has been reported in literature that more than 5000000 persons are living with paralysis, in the USA only, and about 1,000,000 people are completely unable to move without assistance [1]. According to recent surveys, the annual cost of health care provided to those individuals with disabilities exceeds US$300 billion. According to the same source, in most of the cases the cause of paralysis is spinal cord injury (SCI) caused by road accidents and violence. More than 50% of these individuals with severe disabilities are below 30 year old and need lifelong special care services for the rest of their lives, provided by more than 50,000,000 health care specialists [2]. Therefore, the research community has been trying to address the issue of people with severe disabilities in order to improve their quality of life and reduce cost of health care. Research has been conducted to develop advanced wearable assistive technologies that help improving life of individuals living with complete paralysis by taking advantage of recent advancements in information technology and wireless communications. These assistive technologies allow those persons with severe paralysis to interact and communicate with other devices such as television set, radio, wheelchair, computer, laptop, and tablets. The objective is to augment the remaining abilities of a person living with severe disabilities to perform limited activities.

In the following section we present a brief literature review of the technology.

II. Literature Review

As reported in literature, noninvasive and invasive Brain Computer Interfaces (BCIs) that use electrode arrays to capture and record brain activity and send signals to a computer for further processing and actions, have been developed and analyzed on non-human and human subjects [3-5]. However, these technologies have not become popular among user due to the high cost of equipment and other technical issues such as the electrode lifetime, maintainability, robustness, reliability, and vulnerability to ambient noise and interference.

Since the majority spinal cord injury patients have normal facial expressions, vision, and speech, noninvasive technologies such as eye trackers, head pointers, speech recognition devises have been proposed and studied [7]. However, the eye tracker device may interfere with the subject vision filed, the head pointer device neck and shoulder muscle pain, and a speech recognition device not effective in a noisy environment. Therefore, new advanced low cost, noise tolerant, effective, user friendly technologies that offer broad coverage among SCI patients in various environments and provide wide communication bandwidth are absolutely needed.

Since the mouth and the tongue are noninvasively accessible, the tongue can move rapidly and accurately, within the oral cavity, in a motion that is not influenced by the position of the rest of the body and sine the tongue is capable of accomplishing manipulation tasks with many degrees of freedom, then a tongue-computer controlled based device is an attractive solution to be studied [6, 8].

The following tongue based assisted technologies, Tongue-Touch-Keypad, Tongue-Mouse, Tongue-Point, Mmouth-joystick devices have been developed and reported in literature [9-12, 13]. These devices require tongue contact, tongue pressure, and inserting bulky objects inside the mouth, which may interfere with the patient's breathing and may also cause irritation in the mouth if used for a long period of time.

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A magneto inductive sensor-based wireless tongue–computer interface was proposed in [14]. The magnetic wireless tongue-computer interface provides people with severe disabilities with flexible and effective computer access and environment control. The system magnetic field generated by the movement of the tongue are detected by fixed position sensors are transmitted wirelessly to a computer for processing and translation into control commands used to control devices in a given environment such as a powered wheelchair.

A tongue-operated, minimally invasive, and wireless tongue drive assistive technology was reported in [15]. The proposed assistive wireless system senses and classifies tongue motions and translates movements into user-defined commands. Interaction time with controlled device depend on the number of commands to be processed.

This paper is organized as follows: the proposed Tongue Drive System (TDS) representation is explained under Section III and the mathematical model of the TDS is discussed under Section IV. In Section V, hardware scheme along with the functionalities of each component of the TDS is discussed. Finally, concluding remarks together with the future considerations for TDS are highlighted in Section VI.

III. Methodology

The proposed Assistive TDS uses multiple magnetic sensors and capable of detecting the position and movement in three dimensional space of small size piercing (magnetic tracer) attached to the subject tongues. The overall system representation is shown below in Figure 1.

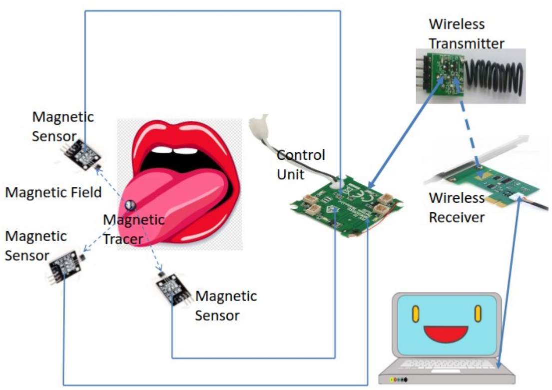

Fig. 1. System representation

The system uses an array of magnetic sensors positioned and mounted properly around the user's head; those sensors detect tongue motion (magnetic tracer is spherical permanent magnet of approximately 2.5 mm in diameter) and measure differential changes in the magnetic field around the mouth. Magnetic field is then packaged into data packets, which are transmitted wirelessly at a rate of 300 Mbits/second to a laptop for interpretation, translation into user predefined computer commands, and actions.

Analog data from sensors are digitized and sampled at a rate of 15Hz when tongue is in motion while data is sampled at 1.5Hz when tongue is at rest. A small control unit (raspberry pi 3 module) is used to switch ON/OFF the magnetic sensor modules; one sensor is activated at a time and transmitting unit is turned OFF when tongue is in standby mode, in order minimize power consumption.

Incoming sampled data are further processed at the receiving workstation, key features are extracted, and sensor signals are translated into computer commands when the system is in training mode. When the user moves their tongue to particular positions in space, the system recognizes the issued commands, and then commands are executed in real-time.

System prototype will be tested and validated on both male and female SCI patients between the age of 18 and 66-year-old. We will select users with some computer knowledge, limited computer knowledge, and completely new to computers. System trials will be carried out after obtaining consent from all subjects.

System prototype functionalities will be assessed in terms of system response time and data transfer rate as well as user interface friendliness. In the following section we present system model.

IV. Mathematical Model

In this section we briefly describe the theory behind different modules and functions used in this technology.

A. Magnetic induction signal generation

The magnetic induction intensity B at an arbitrary given point P(ρ, θ, z) around a single magnetic sensor, in a circular cylindrical coordinates (ρ, θ, z) can be represented as shown below [16].

$$B_\rho = \frac{1}{\rho}\cdot\frac{\partial A_z}{\partial \theta} - \frac{\partial A_\theta}{\partial z} = -\frac{\partial A_\theta}{\partial z} = -\frac{\partial A_\theta}{\partial k}\cdot\frac{\partial k}{\partial z} = \frac{\mu_0 I}{2\pi}\cdot\frac{z}{\rho}\cdot\frac{-K(k)+\frac{R^2+\rho^2+z^2}{(R-\rho)^2+z^2}\cdot E(k)}{\sqrt{(R+\rho)^2+z^2}}, \tag{1}$$

$$B_\theta = \frac{\partial A_\rho}{\partial z} - \frac{\partial A_z}{\partial \rho} = 0, \tag{2}$$

$$B_Z = \frac{1}{\rho}\left[\frac{\partial}{\partial \rho}(\rho A_\theta) - \frac{\partial A_\rho}{\partial \theta}\right] = \frac{1}{\rho}\frac{\partial(\rho A_\theta)}{\partial \rho} = \frac{A_\theta}{\rho} + \frac{\partial A_\theta}{\partial \rho} = \frac{\mu_0 I}{2\pi}\cdot\frac{K(k)+\frac{R^2-\rho^2-z^2}{(R-\rho)^2+z^2}\cdot E(k)}{\sqrt{(R+\rho)^2+z^2}}. \tag{3}$$

The magnetic induction B converted into a rectangular coordinates system (x, y, z) has three components (B_x, B_y, B_z), represented by the projection of B along the X, Y, and Z axis, and therefore B can be expressed as a function P(x, y, z) in space B = *f* [P(x, y, z)].

As shown in Fig. 2, the three magnetic sensors are positioned in a 3D space and they are orthogonal to each other.

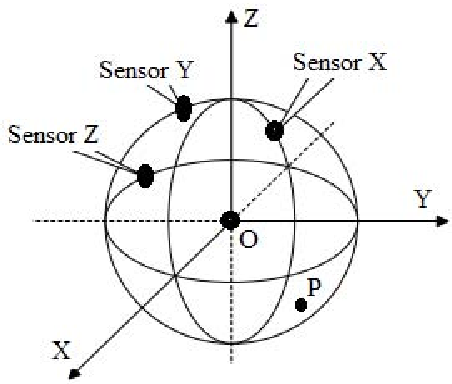

Fig. 2. 3D space representation

The magnetic field is generated by the three magnetic sensors in given period of time, operates in time division mode, and they follow the direction of the (x, y, z) axis.

Based on the computation model of a single sensor Z, we can derive the equation of the magnetic induction intensity BX and BY for sensor X and Y at any given point P(x, y,z) in the surrounding space. The equations BX, BY, and BZ can be expressed as:

$$BX = f[P(x, y,z) . Ty(-90^\circ)] . Ty(90^\circ) \quad (4)$$

$$BY = f[P(x, y,z)\cdot . Tx(90^\circ)] . Tx(-90^\circ) \quad (5)$$

$$BZ = f[P(x, y,z)] \quad (6)$$

where Tx(·) and Ty(·) represent the angular rotation around the X- and Y-axis according to right-hand-screw rule. BX, BY, and BZ have three components (BXx, BXy, BXz) along the X, Y, and Z axis.

B. Wireless signal transmission and reception

Wireless channel is characterized as a multipath channel due to signal reflection from fixed and moving objects. Signal multipath component undergo time varying propagation delay. Therefore, the channel can be mathematically modeled as a linear filter characterized by time variant channel impulse response as follows:

$$r(t) = s(t) * c(\tau, t) + n(t) \quad (7)$$

$$= \int_{-\infty}^{\infty} c(\tau, t) . s(t - \tau)\, d\tau + n(t) \quad (8)$$

Where $r(t)$ represents the received signal, $s(t)$ is the transmitted signal, $c(\tau, t)$ is the response of the wireless channel at time t due to the impulse applied at time $t - \tau$, and $n(t)$ is the added noise. Figure 3 shown below depicts a linear time variant filter with additive white Gaussian noise.

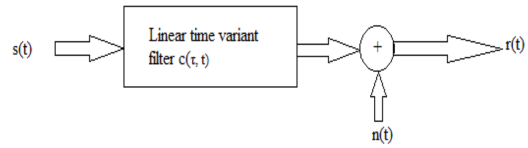

Fig. 3. Wireless channel

At the receiving end, the received signal $r(t)$ is equal to the estimated transmitted signal $s_m(t)$ plus the added noise $n(t)$ such as $r(t) = s_m(t) + n(t)$. The receiver module consists of a demodulator, matched filter, and detector. The received signal $r(t)$ can be decomposed into a series of linearly weighted orthogonal basis functions as follows:

$$r_k = \int_0^t r(t) . f_k(t)\, dt = \int_0^t [s_m(t)+n(t)] . f_k(t)\, dt \quad (9)$$

for $k = 1, 2, 3, \ldots, N$

$$s_{mk} = \int_0^T s_m(t) . f_k(t)\, dt \quad (10)$$

$$n_k = \int_0^T n(t) . f_k(t)\, dt \quad (11)$$

The matched filter $h_k(t)$ can be represented by

$$h_k(t) = f_k(T - t) \text{ for } 0 \le t \le T \quad (12)$$

Therefore, the output of the filter is given by:

$$y_k(t) = \int_0^T r(t)\, h_k(t - \tau)\, d\tau \quad (13)$$

$$= \int_0^T r(t)\, f_k(T - t + \tau)\, d\tau \qquad \text{for } k = 1,2 \ldots N$$

The role of the detector circuit $D(r, s_m)$ is to make a decision on the transmitted signal in each signal time interval based on observation.

$$D(r, s_m) = ||r||^2 - 2rs_m + ||s_m||^2 \quad (14)$$

for $m = 1,2,\ldots,M$

C. Signal processing

The nature of magnetic induction signals is continuous both in amplitude and time. Modern data acquisition and analysis frequently depend on digital signal processing, and therefore the signal must be converted into a discrete representation. The time scale is made discrete by sampling the continuous wave at a given interval; the amplitude scale is made discrete by an analog-to-digital converter (ADC).

An important characteristic of an ADC is its amplitude resolution, which is measured in bits. Usually in biomedical equipment, converters have at least a 16-bit range (2^{16} = 65,536 levels) for high accuracy. The resolution of the complete conversion process is expressed as step [µV] per digitizer unit [bit], also depends on the analog amplification. After the signal samples are converted, data is stored as real numbers (bytes) for further processing.

D. Pattern matching

A wavelet-based pattern recognition algorithm that works on the incoming data from magnetic sensors is used to detect tongue movement and match it with predetermined patterns stored in library. We have constructed five patterns, one for each transition (between stable, right, up, left, and down); to be able to detect and infer the current tongue position. Tongue movement detection is realized using a wavelet-based pattern recognition algorithm, which has been applied in a large variety of applications, ranging from hand-written to printed characters recognition [17].

The filtered signal goes through a segmentation process to determine the possible positions of the tongue transitions. While occurring a tongue transition, the variations of the magnetic sensor voltages are higher. The segmentation is done by analyzing the standard deviation of the norm of the sensors.

For different tongue movements, the respective standard deviation s_{ass} and s_{all}, are computed, allowing to make a logical decision. At a given window number i and standard deviation s_i as follows:

$$\text{Segmentation}_i = \begin{cases} 1 \text{ if } 0.5 \cdot s_{ass} \leqslant s_i \leqslant 1.5 \cdot s_{ass} \\ 2 \text{ if } 0.5 \cdot s_{all} \leqslant s_i \leqslant 1.5 \cdot s_{all} \\ 0 \text{ else} \end{cases}$$

The threshold of detection with half more or less of the initial values have been chosen by running preliminary experimentations to reduce the number of false detections.

We define a function ψ, well localized in frequency and time space, and a base from this function by translating and dilating it as follows:

$\psi_{a,b}(t) = 1/a\ \psi(t-b/a)$, with a>0

and computing the coefficients of the transformation of the signal x(t)

$$\text{with } C_{a,b} = \int_{-\infty}^{+\infty} x(t)\ \psi_{a,b}(t)dt$$

Figure 4 gives the confusion matrix of the aforementioned pattern matching algorithm during the testing phase.

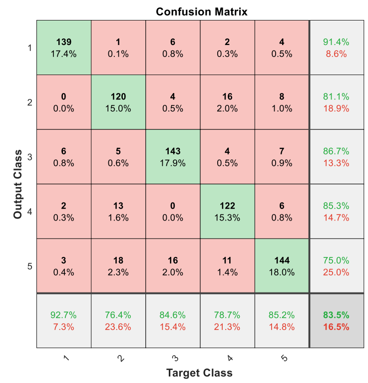

Fig. 4. Confusion Matrix for Tongue Gesture

Note the following classes:
Class 1: stable or no tongue movement pattern
Class 2: upward pattern
Class 3: downward pattern
Class 4: right hand side pattern
Class 5: left hand side pattern

V. Hardware Arrangement of TDS

Figure 5 shows the hardware scheme of the TDS where by all the main components are depicted in red. The process starts from acquiring the signals from the magnetic sensors and then transferred to the control module which determines whether the oncoming signal is a legitimate tongue gesture. Thereafter, the DSP module filters this signal and analog to digital conversion as explained under Section IV.C. Via Bluetooth module, the filtered signal is then transmitted to the receiving end which governed by the Android Device. Signal Classification is done within the Android Device which then outputs the correct gesture of the tongue via display and by means of a speaker. Following subsections will describe the specification and function of each module in Fig. 5.

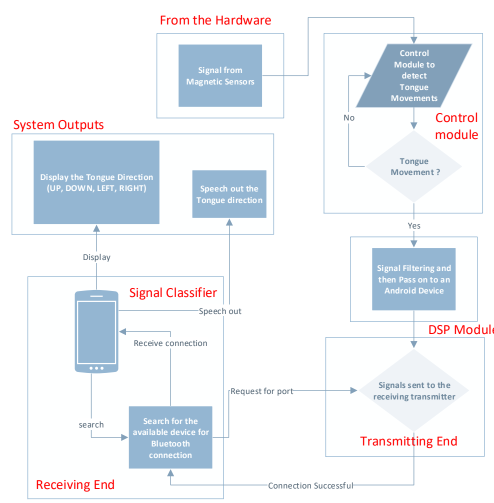

Fig. 5. Hardware Scheme for TDS

A. *Sensor placement and its function*

Three magnetic sensors are placed as shown in Fig. 6. The sensors placed on the LHS and RHS are used to detect movement of the tongue for east and west directions, respectively. Another magnetic sensor is placed orthogonal to the other sensors which accounts for the movement in north and south (see Section IV.A for the modelling). A major part is played by the magnetic tracer (a spherical permanent magnet of approximately 2.5 mm in diameter) which in placed in the center. Calibration is a foremost step prior to operating the TDS as the placement of the magnetic tracer will vary from person to person.

Moreover, the sensors are mounted properly around the user's head (using headset like module); these sensors detect tongue motion and measure differential changes in the magnetic field around the mouth. Magnetic field is then packaged into data packets, which are transmitted wirelessly at a rate of 300 Mbits/second to a receiving end for interpretation, translation into user predefined computer commands, and actions.

Incoming sampled data are further processed at the receiving workstation, key features are extracted, and sensor signals are translated into computer commands when the system is in training mode. When the user moves their tongue to particular positions in space, the system recognizes the issued commands, and then commands are executed in real-time.

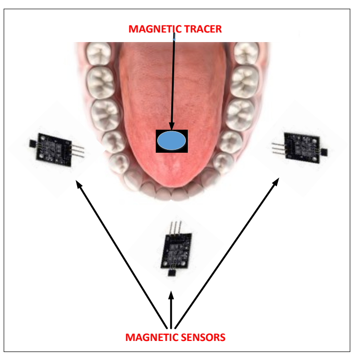

Fig. 6. Sensor placement for TDS

B. *Wireless data transfer*

In this study, the data transfer is achieved through Bluetooth communication. As per Fig. 5, after the signal has been filtered, it is transmitted to the Android device via Raspberry Pi 3's inbuilt Bluetooth module. The Android device, which has an installed application specifically designed to classify the oncoming signal then classifies the signal in question and gives the output in form of speech and display. To quantify the time delay of the developed system, 300 samples were taken for each class in the testing phase. The duration from acquisition till classification of the oncoming signal (tongue gesture) was measured for each class separately and then averaged. Figure 7 shows the average time delay when classifying all the five gestures. It is actually apparent that the developed system responds faster to the oncoming signal as time delays are less than 0.25s for all the tongue gestures.

The application has been developed using the MIT APP INVENTOR platform which uses the online based sever, meaning the Android device has to be connected to the sever to ensure correct classification for the TDS. This was the only limitation for the proposed TDS however in future it is possible to rely on the TDS without the online based server. Figure 8 illustrates the wireless data transfer scheme.

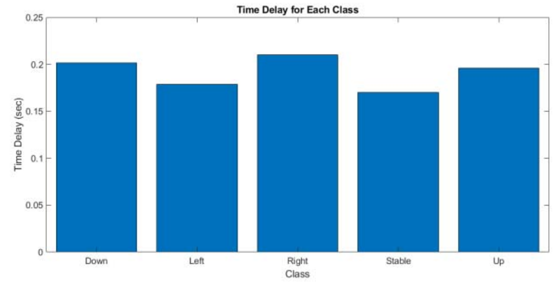

Fig. 7. Time-delay Graph for all the Classes

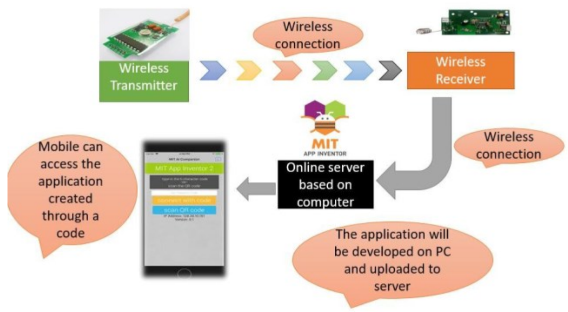

Fig. 8. Wireless data transfer scheme

C. *Headset Design for the TDS*

Considering the number of sensors, the control module and the transmitter, a customized headset is designed for the user of the TDS. Using the notion of the wireless computer headset with mic, the TDS Headset is similarly designed, however having three probes coming out orthogonal to each other for the sensors and the control module along with the transmitter located on top and on one of the earpiece. Figure 9 gives the side view of the TDS Headset and indicates where the magnetic sensors will be placed.

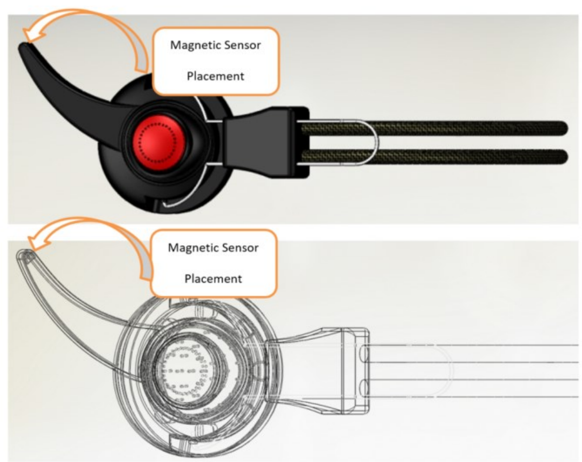

Fig. 9. TDS Headset Side View

VI. Conclusion

After careful consideration of the end user's disabilities, the TDS system provides not only a portable solution but also proposes a new tongue driven language which would enable the students with severe disabilities to interact with the environment and also with other individuals.

The proposed TDS system comprises of three magnetic sensors, a control module (Raspberry Pi 3), transmitter and an Android device with internet connection. The system designed in such a way that would work with any type of Android system and output the tongue gesture in form of speech or display.

The TDS can be extended to control computer mouse, keyboard and also the movement of a wheelchair. In this study, the TDS language is limited to only five classifications (STABLE, UP, DOWN, LEFT, RIGHT). Future studies will involve in extending the current TDS language to a more explanatory and diverse gestures and develop a curriculum for the users to understand better the tongue language.

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