The MouthPad – a Tongue Interface for Hands-Free Computer Control

by

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Abstract

Tongue-computer interfaces allow people with upper limb disability to control a computer with their tongue. A number of assistive devices, that make use of this technology, have been developed in the last two decades: some employ contact impedance, membrane switches, or miniature joysticks, while others use magnetic or piezoelectric sensors.

This thesis proposes a new tongue-computer interface, which was designed to enable users to manipulate a computer pointer by moving the tip of their tongue over an intraoral electrode array. The system maps the contact between the tongue and the electrodes, detects the movements of the tongue, and translates it into pointer movements.

Compared to similar devices, the MouthPad does not require any head gear or sensors, and does not employ heavy signal processing. The hardware is simplified by using a small number of electrodes and only one output channel, multiplexed over the electrode array. A low power footprint allows the potential miniaturization of the system, so that it could fit on palatal retainer, and allow for permanent unobtrusive usage.

The performance of the device was evaluated by measuring the throughput and the accuracy as defined in ISO 9241-9 standard. Two extra measures proposed in the literature, target re-entry and movement offset, were used for the evaluation of the accuracy. The measured throughput values were situated between 78% and 88% of the throughput rates of regular computer joysticks.

Acknowledgments

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Dedication

This is dedicated to my family, for their support and patience.

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Chapter 1

Introduction

1.1 Human-Computer Interaction

The field of human-machine interaction took on a new dimension in the late 1970s, when the personal computer (PC) was introduced to the world. Before the PC interaction with computers was reserved to the professionals of the field. Nowadays everybody has either got a computer or access to a computer, and personal computers are now common place.

Human-computer interfaces have evolved and multiplied, in parallel with the development of the PC and mobile computers. A variety of ways to control computers has emerged: keyboard, mouse, joystick, trackball, touchpad, etc. These devices are only useful for healthy people with normal neuromotor functions.

Alternative directions have been taken in the research of human-computer interfaces. One direction is the development of dedicated computer interfaces for people with special needs. Another one is the diagnosis and rehabilitation of various medical conditions, where biofeedback collection, neurostimulation, and sensory substitution are found among the techniques employed.

1.1.1 Assistive Technology

Computer communication has taken over the world since the advent of the internet and the World Wide Web. Email, online shopping, remote working, video conferencing, and have all become ubiquitous tools in everyday life. Yet there are around two million people in the United States alone [1] that have their neuromuscular channels disabled by some form of medical condition, and therefore have limited or no access to this technology, since they cannot control a computer through regular input devices, like a mouse, or a keyboard.

A way to control computers through alternative channels is what this category of people needs to be able to join the online world, better integrate in society, and improve their quality of life and their job prospects.

Research in the field of assistive technologies for computer control has seen a surge in the last two decades, both in the academia and in the industry. The main purpose of this type of research is to create the means to control a computer without the use of limbs.

A handful of devices have been designed in the field of assistive technology, each of them with their own advantages and disadvantages.

Some of these systems use electroencephalography (EEG) or electromyography (EMG) to detect the user's intentions; others use various types of face or gesture recognition, like nose or tongue movement, or eye gaze. This thesis is dealing with the latter and in particular with tongue gesture recognition.

1.1.2 Diagnosis and Rehabilitation

Biofeedback is a procedure that consists of gathering information regarding biological functions from the subject’s body [2]. The information can be used for the purpose of diagnosis [3, 4], for treatment and rehabilitation, as well as machine control. For example, in the case of paraplegia/quadriplegia, information about the posture of the body is provided, so that the subject would avoid pressure sores formation [5].

Neuromodulation and biofeedback have been employed in the alleviation of certain medical conditions, like vestibular disorders [6], speech disorders [4], as well as in sensory substitution and augmentation [7].

Brain plasticity, or neuroplasticity, is the brain’s capability of restructuring itself, and changing its function; neuroplastic changes can lead to functional recovery after brain damage [8]. Neuroplasticity can be induced through repetitive stimulation of neural networks, a process called neuromodulation [9]; non-intrusive neuromodulation can be through various methods, including intraoral electrical stimulation [10, 11] or transcranial electrical stimulation [12, 13, and 14].

1.2 Intraoral Human-Computer Interfaces

Intraoral human-computer interfaces are generally used as assistive devices, for diagnosis via biofeedback collection, and in neuroplastic rehabilitation initiated through neuromodulation. Among the most commonly used pathways for intraoral electrical stimulation and biofeedback are the palate [4] and the tongue [7].

The tongue has been successfully used as a gateway to the brain, mainly for sensory augmentation and substitution [7], for biofeedback collection, and to provide the users with feedback about their environment. The high resolution of sensory receptors [15], their placement close to the surface [16], the presence of saliva that acts as electrolytic solution [7] as well as the fact that it is connected directly to the brain [17], rather than through the spine, makes the tongue a good candidate for brain interfacing in the case of quadriplegia, blindness, as well as other conditions and disabilities.

1.3 Motivations

A fairly large number of systems and methods have designed for allowing computer control via alternative channels. Most of these devices require external bulky equipment, like the ones that use magnetic sensors. Brain-computer interfaces (BCI) that use EEG or EMG require electrodes to be affixed, and have to employ intensive signal processing. The systems based on eye gaze take up bandwidth on the visual sensory channel that is already used as the main means of input from a computer. Gestures and posture recognition require head movement, and that is not possible for some quadriplegics.

Some of the previous systems were tested for performance, but very few against the ISO standard for human-computer interaction. To be able to determine the real-life feasibility of a human-computer interface, standardized testing should be employed, and the system's performance should be evaluated against a similar device built for able-bodied users.

1.4 Objectives

- Design and build a tongue-computer interface that allows the hands-free control of a computer.
- Test the performance and usability of the system using standardized methods specified in the ISO 9241 standard.
- Benchmark the system against similar devices built for able-bodied users.

1.5 Proposed Solution

The solution proposed here, called MouthPad, involves tongue gesture capturing for the purpose of controlling a computer via a pointing device. Tongue gestures are monitored by measuring the contact between the tongue and an electrode array placed on the palate. The design was inspired by the Tongue Display Unit [16] and by the Palatal Tongue Controller [18].

Other than the intraoral electrode array, the MouthPad requires no external gear attached to the body. By using only one output source, multiplexed over the electrode array, the complexity of the electronics was reduced in comparison with similar systems. The hardware is simple enough to be potentially fitted on a dental retainer; when fitted on a dental retainer it would not be visible and would not impede speech.

1.6 Scope

The purpose of this thesis is to provide proof of concept for a pointer control method that allows a disabled person to use a computer without external gear, and with minimal setup effort.

For the first prototype, an external control unit was used, coupled with a wired tongue device; no miniaturization was planned for this prototype.

The testing was performed only on able-bodied subjects that are experienced computer users.

Chapter 2

State of the Art

Following is a review of human-computer interfaces with emphasis on intraoral devices within the realm of assistive technologies and rehabilitation. The main applications are computer control, biofeedback collection, and neuromodulation.

2.1 Computer Control

Clayton [18] used the Reading Electropalatograph [4] to build an intra-oral controller, where the palate electrodes are used as inputs for communication between the user and a computer, a communication system or a wheelchair; the system is programmed to recognize specific patterns of tongue movement.

The Tonguepoint [19] is a joystick like isometric pointing device, designed by Salem and Zhai from IBM, and based on the IBM TrackPointIII. It is mounted on a mouthpiece and can be manipulated with the tip of the tongue; it has two intraoral switches for button selection, an external switch that can be operated by hand or foot, and can be fitted with a biting switch.

Nutt et al. [20] described a “tongue-mouse” consisting of a piezoelectric ceramic touchpad, fitted on a mouthpiece, and placed on the anterior part of the palate. The user is able to control a mouse pointer on the touchpad with the tip of the tongue; it has a “bitesensor” with three switch points that the user can activate with the front teeth.

The Tongue-Operated Switch Array (TOSA), developed by Kim, Tyler, and Beebe [21], consists of five membrane switches placed on a PCB that can be activated with the tip of the tongue. TOSA has three functional modes: perception (switch location), manipulation (tongue movement), and force application (switch actuation).

Struijk [22] designed an inductive tongue-computer interface by placing five inductors on a mouthpiece placed on the palate, and a magnet on the tip of the tongue. The user would select actions by placing the magnet against the inductors on the palate and activating the inductors.

Krishnamurthy and Ghovanloo [23] developed the Tongue Drive System. A magnet is placed on the tip of the tongue, and inductors are positioned on the outer side of a dental retainer, attached to the teeth on the mandible. The inductors are activated when the magnet is moved close to them, and thus the system is able to detect the relative position of the tongue. The user is able to operate the magnet as a pointer on a computer screen.

A ZigBee based wireless intra-oral control system has been presented by

Peng and Budinger [24], which is a simplified version of the Tongue Touch Keypad, with five buttons, used to control external devices, like computers. It has the advantage of low power consumption and a wider wireless range.

Kelly and Schwartz [25] have used infrared proximity sensors to detect the motion of the tongue, for the purpose of taking mouse and keyboard input. The sensors consist of four pairs of IR LEDs and IR sensitive photodiodes attached to a palatal mouthpiece. When the tongue is in the close vicinity of a LED-diode pair, the light emitted by the LED is reflected into the diode, causing a voltage across the diode that allows the device to detect the presence of the tongue.

Many face recognition devices have been developed [26, 27, 28, 29, and 30]. This is probably due to the fact that they are software based, and in general the only hardware required is a web camera, which is easily accessible.

2.2 Biofeedback and Sensory Substitution

The Reading EPG3 system [4] is an electropalatograph with 62 silver electrodes mounted on palatal mouthpiece. The Reading electropalatograph is able to dynamically record the contact between the tongue and the palate during continuous speech, by reading the contact impedance between the tongue and the electrodes after sequentially sending a pulse through all the 62 electrodes; it is used in the assessment and treatment of speech disorders.

Loudon and Stillman [31] built an electrogustometer that that can be programmed via a JTAG interface from an IBM-PC station. It is essentially a programmable bidirectional dual channel current supply, controlled by software running on the PC workstation, via a feedback loop. The electrogustometer is used to measure evoked taste thresholds.

Fitzsimmons et al. [32] have designed an electrical taste stimulator and its interface to an evoked potential recording unit. The stimulator is an electrogustometer with an adjustable current source with the anode electrode placed on the tongue, and the cathode one placed under the tongue. The system has a tactile stimulation unit for the top of the tongue, consisting of a lever action solenoid connected to 12V DC, activated by a separate switch and a timer circuit. Electrical and tactile stimulation can be provided separately or simultaneously. The stimulator is connected to an off-the-shelf evoked potential recording system that records brain potentials elicited by the stimulation.

An electrotactile display has been developed by Bach-y-Rita et al. [16] to study form perception with the tongue. The device, later called Tongue Display Unit [33], is an array of 7 x 7 round electrodes placed on the tip of the tongue. The TDU has been used for proof of concept for vision substitution via the tongue. Extended to 12 x 12 electrodes [7], the TDU has been successfully used as a portable vision substitution solution [34].

Tang and Beebe [35] have designed a flexible electrotactile display with 7 x 7 domed electrodes, to be used for vision substitution on the palate.

They have later [36] improved its design by placing it on a mouthpiece and adding a Tongue Touch Keypad on the bottom; the Tongue Touch Keypad (TTK) is allowing for bidirectional communication by taking commands from the user through nine keys placed on the bottom of the mouthpiece.

Tyler et al. [6] have used the TDU in combination with a 2-axis accelerometer to help subjects with vestibular conditions improve their posture. The accelerometer was placed on a hard hat worn by the subject. The longitudinal and lateral movement data provided by the accelerometer were supplied via the TDU, allowing the subject to correct its posture accordingly.

A system was designed by Moreau-Gaudry et al. [37] to compensate for sensory loss in paraplegics and avoid the occurrence of pressure sores. The system consists of the TDU, a pressure mapping system and a controlling laptop. Biofeedback regarding the pressure exerted between the skin and the seat was provided via the tongue display, allowing the subjects to adjust their posture accordingly.

The TDU has also been used in conjunction with a plantar pressure data acquisition system (FSA Inshoe Foot) by Vuillerme et al. [38], to provide improved balance control. Pressure data provided by the FSA Inshoe Foot system was translated into "visual" cues actuated onto the subject's tongue by the TDU, allowing them to improve their posture.

Sun et al. [3] have proposed the use of the tongue's impedance for tongue cancer detection. They have shown that, at certain frequencies, there is significant difference between the bioimpedance of cancerous and that of normal tissue.

2.3 Neuromodulation by Electrostimulation

Wildenberg et al. [10, 11] have shown that the electrical stimulation applied to the anterior tongue improves the rehabilitation of subjects suffering from balance dysfunction, without the actual use of feedback regarding the spatial position of the subject's body. This suggests that the electrical stimulation alone can induce neuromodulation in the vestibular neural networks. Stimulation has been applied using an array of 144 electrodes, and consisted of bursts of three monophasic square pulses.

Chapter 3

System Description

This first prototype was conceived for the research of human-computer interfacing, electrical stimulation and biofeedback collection. It is a multifunctional platform that has the ability to deliver multiple types of electrical signals to the human body, and to collect biofeedback (i.e. impedance) from various locations on the body.

3.1 Hardware Implementation

The system consists of a controller unit designed around a microcontroller unit (MCU), transcranial electrodes, and a tongue device featuring an array of gold plated electrodes. An overview of the system is shown in Figure3.1.

Since the system was built for research purposes that involve human trials, and interacts directly with humans, there were safety concerns that led to certain specific power supply and connectivity requirements. One of the main concerns was the connection to the power grid that is a source of electroshock hazard. The decision was made to avoid any connection, direct or indirect, to the power grid. The power had to be supplied by batteries, and the connection to the controlled computer had to be wireless. For cost and availability reasons, a pack of four 1.5 V AA batteries was chosen to provide power for the controller unit, while for the wireless link a Bluetooth chip was selected; Bluetooth was preferred over Wi-Fi for lower costs, simplicity of implementation, and availability.

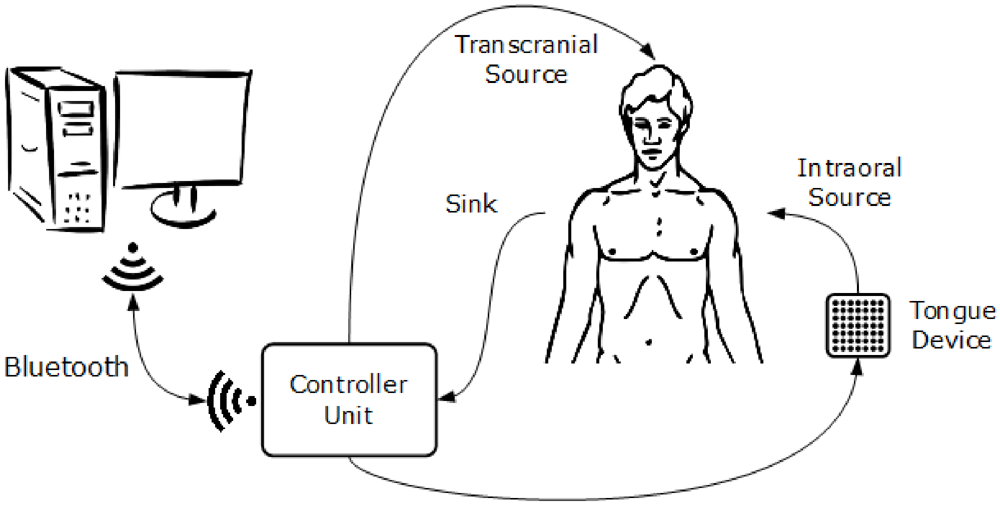


Fig. 3.1 System overview

The collection of bio-impedance measurements implies the presence of an analog-to-digital converter (ADC). To save power and simplify the design, a low power microcontroller with an integrated 12-bit ADC module was selected to run the firmware for the controller unit: the MSP430F5438A from Texas Instruments. The MCU is clocked at 4 MHz using a 32 kHz quartz oscillator.

A front-end application runs on the host computer (desktop, laptop, tablet, or smart phone), and communicates via Bluetooth with the controller unit. The back-end firmware running on the microcontroller manages the biofeedback collection and the electrical stimulation, and supplies the information to the front-end software.

3.1.1 The Controller Unit

The controller comprises of microcontroller, power supply, signal generator, switching fabric for electrode selection, signal conditioning module for biofeedback collection, safety module for monitoring the current level, and Bluetooth module for wireless communication. The simplified block diagram of the controller unit is shown in Figure3.2.

The power supply employs a battery pack of four 1.5 V AA batteries, a power regulator, a voltage reference, and a DC-DC step-up converter. The regulator supplies a stable 3.3 V source for the microcontroller, while the voltage reference provides an external 3 V reference for the microcontroller’s analog-to-digital converter. The step-up converter supplies up to $^{+}/_{-}$ 15 V for the chopper amplifier to drive the output signal.

Various types of wireless transmission protocols and frequencies have been shown to work within the oral cavity: ZigBee [24], Wi-Fi [66], and RFID [67]. Bluetooth has been selected for the wireless communication for a combination of factors, including ease of implementation, low cost and low power consumption. The Bluetooth chip is connected to one of the UART serial ports of the microcontroller. The RN42 Bluetooth chip from Roving Networks was selected to meet the low power requirements

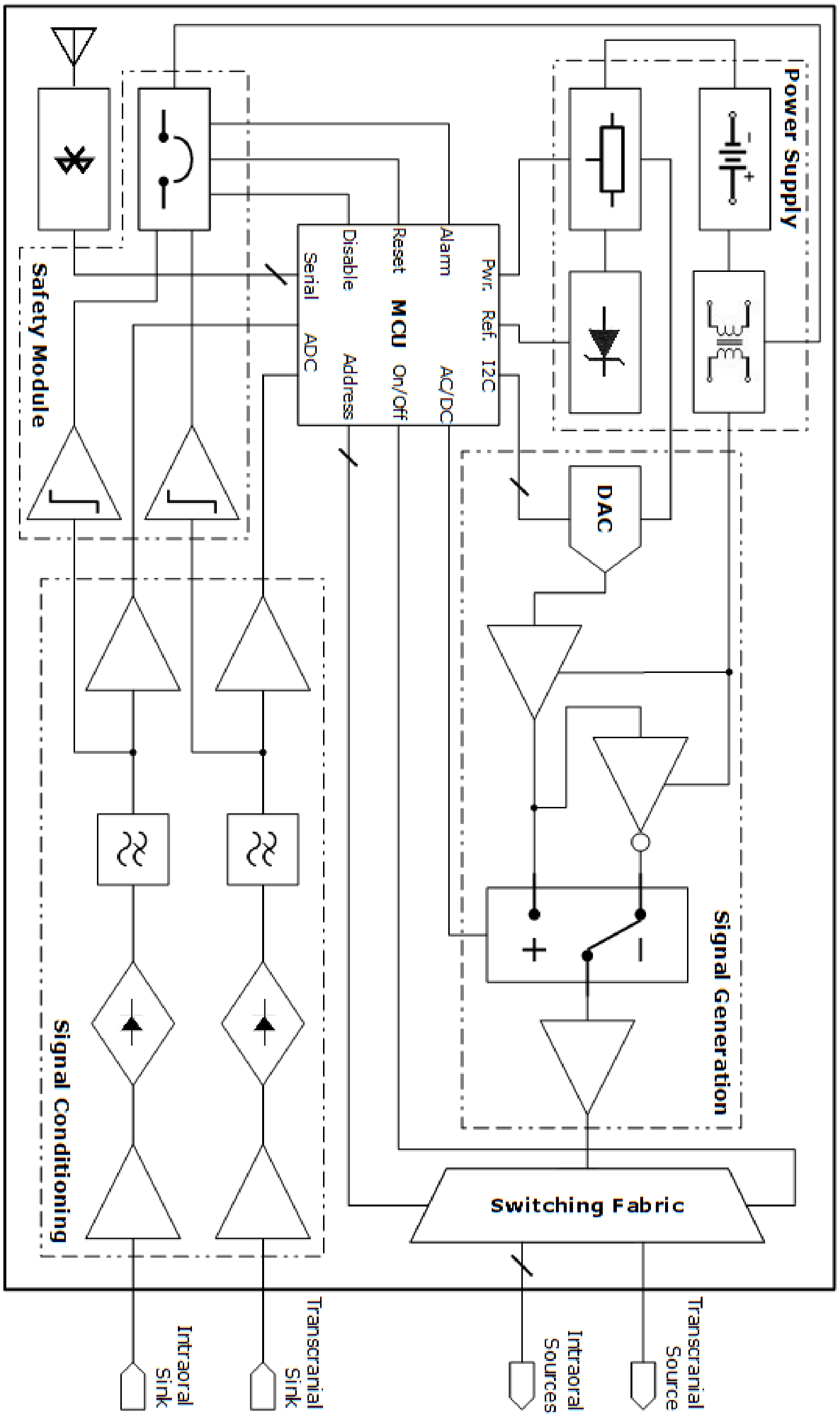


Fig. 3.2 The block diagram of the controller unit

of the controller unit; the chip has serial communication capabilities, an on-chip antenna, and a Bluetooth stack that includes a host controller interface (HCI).

The signal generator module provides the current used for stimulation and bioimpedance measurements. A DC signal generated by the digital-to-analog converter (DAC) is amplified and inverted to provide both the positive and the negative voltage for the signal chopper's inputs. The signal chopper consists of a multiplexer that selects between positive and negative DC. By toggling the logic control input of the signal chopper from the MCU, a square wave signal can be produced, at the desired frequency and duty cycle.

The output channels are selectable via the electrode switching fabric (Figure 3.3). The switching fabric consists of a decoder, level shifters, and analog demultiplexers, with the addressing controlled from the MCU's I/O ports. The electrode address is composed of two 3-bit addresses, referred to as "row" and "column" addresses, for a total of 64 discrete channels. One address is used by the transcranial electrode and 49 by the intraoral electrodes. The row address enables via the decoder one of the seven demultiplexers at a time, and the column address selects the one of the eight addresses available through that respective row demultiplexer.

The two hex level shifters shift the MCU logic signals (electrode address, enable, and signal chopper switch) from TTL levels to the CMOS levels required by demultiplexers that drive the output signal to the intraoral electrode array and the transcranial electrode.

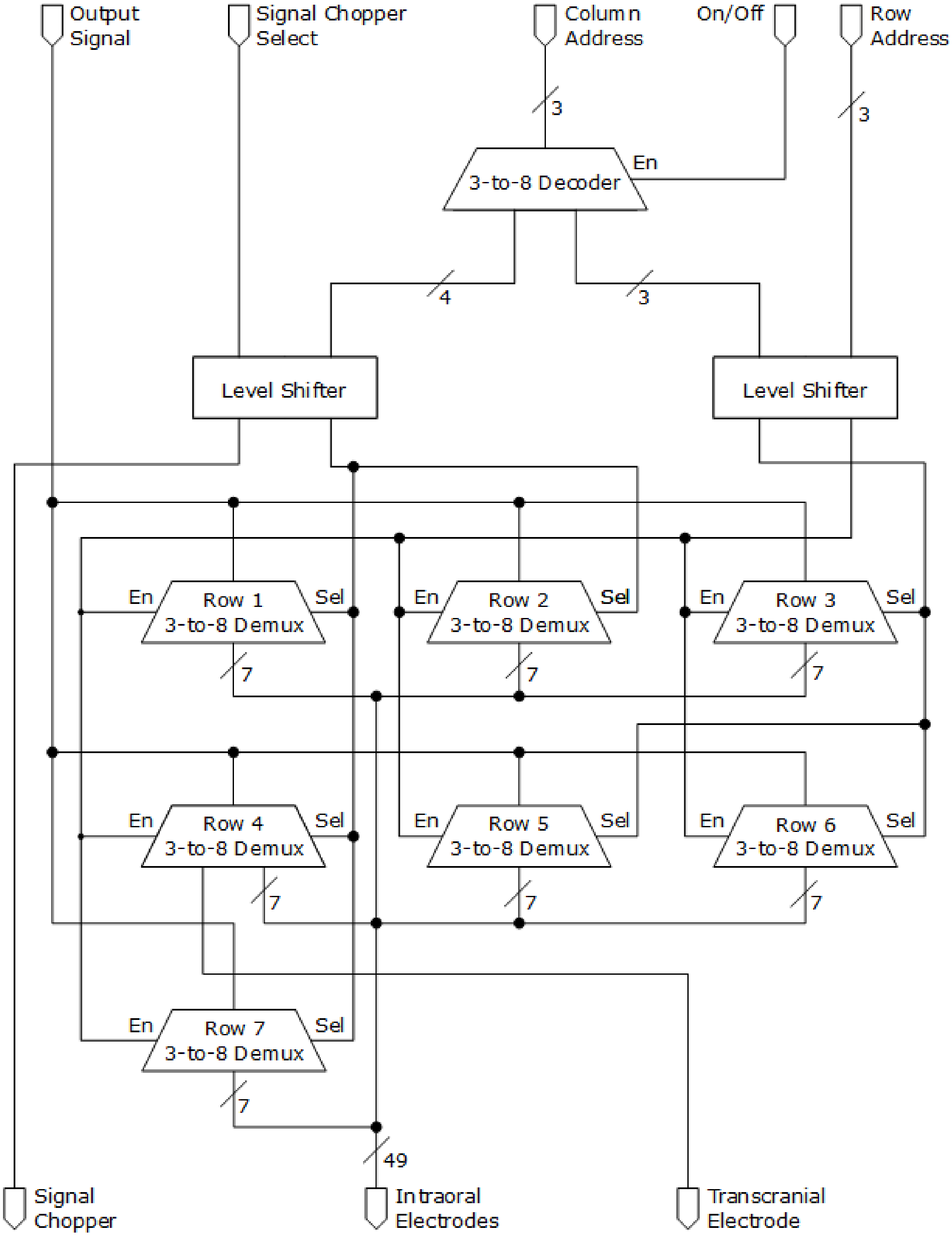


Fig. 3.3 The block diagram of the switching fabric

The amplitude of the output signal is controlled on the DAC from the MCU, via an I^2C connection; alternately, the signal level can also be adjusted through a potentiometer located on the controller unit. This allows for the adjustment of the signal's amplitude to a level below the perception threshold of the respective user, which might be necessary either for sham trial sessions, or simply for the user's comfort.

The frequency can be set via the software interface; however, this feature was not implemented in the user interface for all the applications. For some applications (e.g. MouthPad) the frequency is hard coded, since variable frequency is not a requirement for these implementations. The maximum achievable frequency is50 kHz, while the maximum amplitude is $^+/_-$ 15 V peak to peak, which falls within the range used in similar research projects [39, 40].

The output signal can be actuated through the transcranial electrode and through all, or just a subset, of the 49intraoral electrodes. The transcranial channel can be used simultaneously with the intraoral channel, while the signal is time multiplexed over the 49 intraoral electrodes. A multiplexed approach was preferred over individually driven outputs, due to simpler signal driver hardware and lower power consumption.

The return path for the output voltage signal can be either intraoral or transcranial, that is the return electrode can be either inside, or outside the oral cavity.

For impedance measurements, the MCU's integrated analog-to-digital converter (ADC) is used to sample the signal on the two return paths, the intraoral sink and the transcranial sink. The signal is prepared for analog-to-digital sampling in the signal conditioning module. This module consists of full wave rectifiers, RC single pole low-pass filters and buffers.

The level of the current is monitored with the comparators in the safety module on both return paths, and if the current reaches the safety limit, the safety module cuts the power off for the output by disabling the converter, and triggers an interrupt on the MCU. The maximum current allowed is 2mA for transcranial and 0.2 mA for intraoral currents; these limits are within the accepted safety limits for both intraoral [7, 41] and transcranial applications [13, 14, 42, 43].

Using a transcranial electrode in conjunction with an intraoral or transcutaneous return electrode can be dangerous. The maximum transcranial current is higher than the intraoral one, and the current could inadvertently stimulate the brainstem, which is considered to be dangerous [44]. To avoid the inadvertent use of the system in such a way, extra safety measures were adopted. The part of the signal generator responsible for transcranial current requires a resistor to be soldered and jumper to be fitted, before any signal can be generated.

There are four LEDs on the controller unit that provide information about the state of the system: power-on is signalled by the green LED, the blue one shows the status of the Bluetooth chip, the amber activity LED is on when there is current outputted through any of the electrodes and is also used to signal errors, and the red one is turned on whenever the battery voltage drops close to the minimum input required by the voltage regulator.

3.1.2 The Tongue Device

An electrode array consisting of 49 electrodes, placed on a printed circuit board, shown in Figure3.4, is used to actuate electrical current onto the surface of the tongue. The stimulation electrodes are disposed in a matrix format, seven rows by seven columns. The tongue device has neither sensors or switches, nor electronic components.

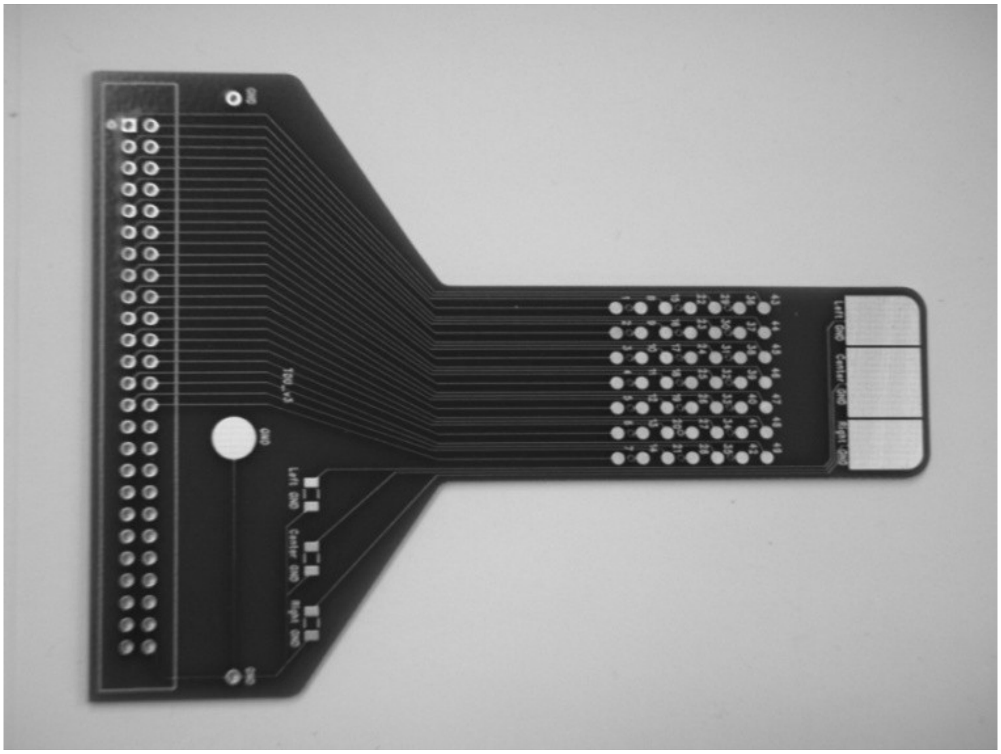


Fig. 3.4 The intraoral electrode array on the tongue device

For the intraoral return electrode, multiple configurations are available.

There are three return electrodes of equal sizes, situated at the tip of the tongue device (Figure3.4), corresponding to the posterior part of the tongue; they can be used individually, or grouped as one single electrode. These three return electrodes were placed on the tongue device to allow research related to the influence of the electrode size on the perception of patterns.

A transcutaneous return electrode can also be used in conjunction with the tongue device, as long as it is not placed on the head, as this is deemed potentially dangerous [44].

The Tongue Display Unit used in the BrainPort device [16] was considered to be a good starting point for a first prototype, since its format and size have been proven adequate for sensory substitution [33] and cranial nerve electrical stimulation [10, 11]. Since tongue position and movement detection is one of the main applications of this system, the spacing between electrodes was increased to create a larger area of contact that allows for more ample tongue movements, which are easier to capture.

The disc shaped flat top electrodes have a diameter of 1.5 mm, with an area of 2.25 mm^2, and the spacing between the electrodes is of 3 mm center to center. The electrodes are gold plated copper; the plating was done using electroless nickel immersion. Gold plating was chosen for the electrodes as the safest affordable option for intraoral usage.

3.2 Software Implementation

The software and firmware presented here were developed for the tongue-computer interface. The other available applications are running different versions of the software and firmware applications.

3.2.1 The Front End

A Java software application was developed in Eclipse for testing the performance and the usability of the system. The application interprets the sequence of snapshots of the contact between the tongue and the electrode array, and translates them into cursor moves. The most recent point of contact between the tongue and the electrode array is mirrored by the mouse cursor on the display of the host computer.

The joystick algorithm is shown in Figure 3.5. A Bluetooth connection must be initiated by the user. At the start of every session, the front end places the back end in "Scanning" state (see Section 5.1.1) by sending a "start" message (see Section 3.2.3). Requests for the contact map are periodically sent to the controller unit, and processed upon receipt. The contact map information is processed, and the pointer is moved accordingly on the screen. Once the session is over, a "stop" (see Section 3.2.3) message is sent to the controller to place it in idle state. If too many communication timeouts occur during the session, the session is interrupted and the user is notified.

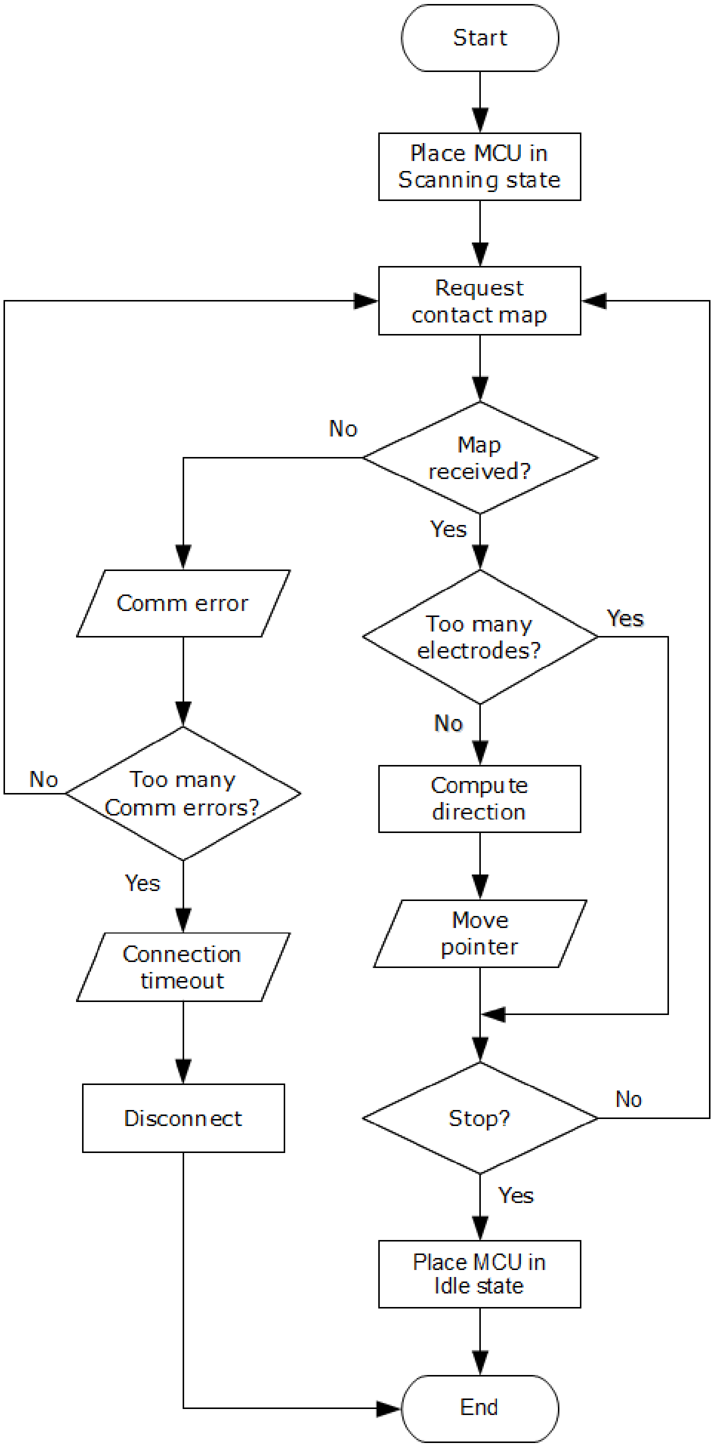


Fig. 3.5 Software algorithm - joystick mode (simplified)

The cursor movement employs an acceleration algorithm. The longer the tongue stays in contact with a particular set of the electrodes, the faster the cursor moves, up to a set maximum speed limit. The acceleration is implemented as an arithmetic progression.

A graphic user interface (GUI) allows the user to display the contact between the tongue and the electrode array, for the purpose of system testing and calibration. The front end application can run various performance tests, as defined in ISO 9241-9, and log the results into spreadsheets, for further analysis.

While performing the functions available in the software, miscommunication with the firmware running on the controller unit might occasionally occur. In these cases the GUI will display specific error messages, and if the number of errors surpasses a set limit, the Bluetooth connection is interrupted and the user is notified of the problem.

3.2.2 The Back End

The controller unit is running a firmware application developed in C, on IAR Embedded Workbench. The firmware on the microcontroller is a bare metal type of application running a round-robin scheduling algorithm, with interrupts and fixed priorities.

The main state machine is shown in Figure 3.6. The MCU is initialized, and then placed in idle state, in sleep mode for power saving. It is only waken up periodically to check the battery voltage, and when interrupts are raised by the UART subsystem for communication purposes. When a message is received from the front end, the back end is placed in "communication" state and the message is processed; if any parameter values are received from the front end, the respective parameters (e.g. contact threshold) are set, and the MCU is sent back to idle state. If a "start" command is received, the back end goes into "scanning" state and awaits requests from the front end. If a "stop" command is received in "scanning" state, the back end goes to idle state.

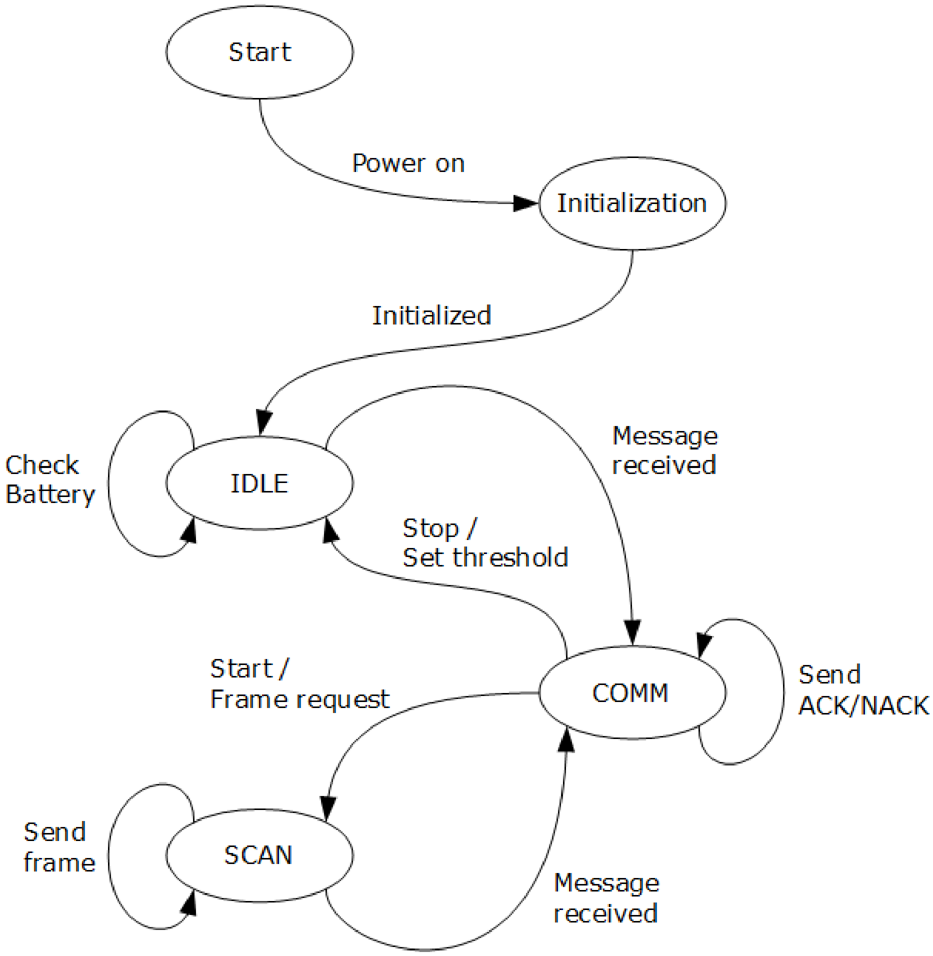


Fig. 3.6 Firmware state machine (simplified)

Figure 3.7 represents the communication state algorithm. This is the pivoting point of the firmware, since the MCU is the slave device and depends almost entirely on the messages received from the host computer. The buffer is checked for new bytes, the new message is processed, and if a parameter value is received (i.e. data in the communication protocol) the respective parameter is set with the new value; if a command is received, the MCU is placed in the appropriate state.

When in the electrode scanning state (Figure 3.8), the MCU is listening for requests from the front end. When a request is received, a timer is started; the timer interrupt service routine (ISR) is responsible for multiplexing the output signal over the electrodes used in the joystick mode.

A flowchart of the electrode array scanning algorithm, performed within a timer interrupt service routine, is presented in Figure 3.9. Within the ISR, after enabling the output for the respective electrode, the return signal is sampled by the ADC module, and if the value is above the set threshold, it is marked in the contact map as connected. After contact information is obtained for all the electrodes, the timer is turned off, and the contact map is sent to the front end. If in calibration mode (see Section 5.1.1.2), the contact map is returned even if there is no contact.

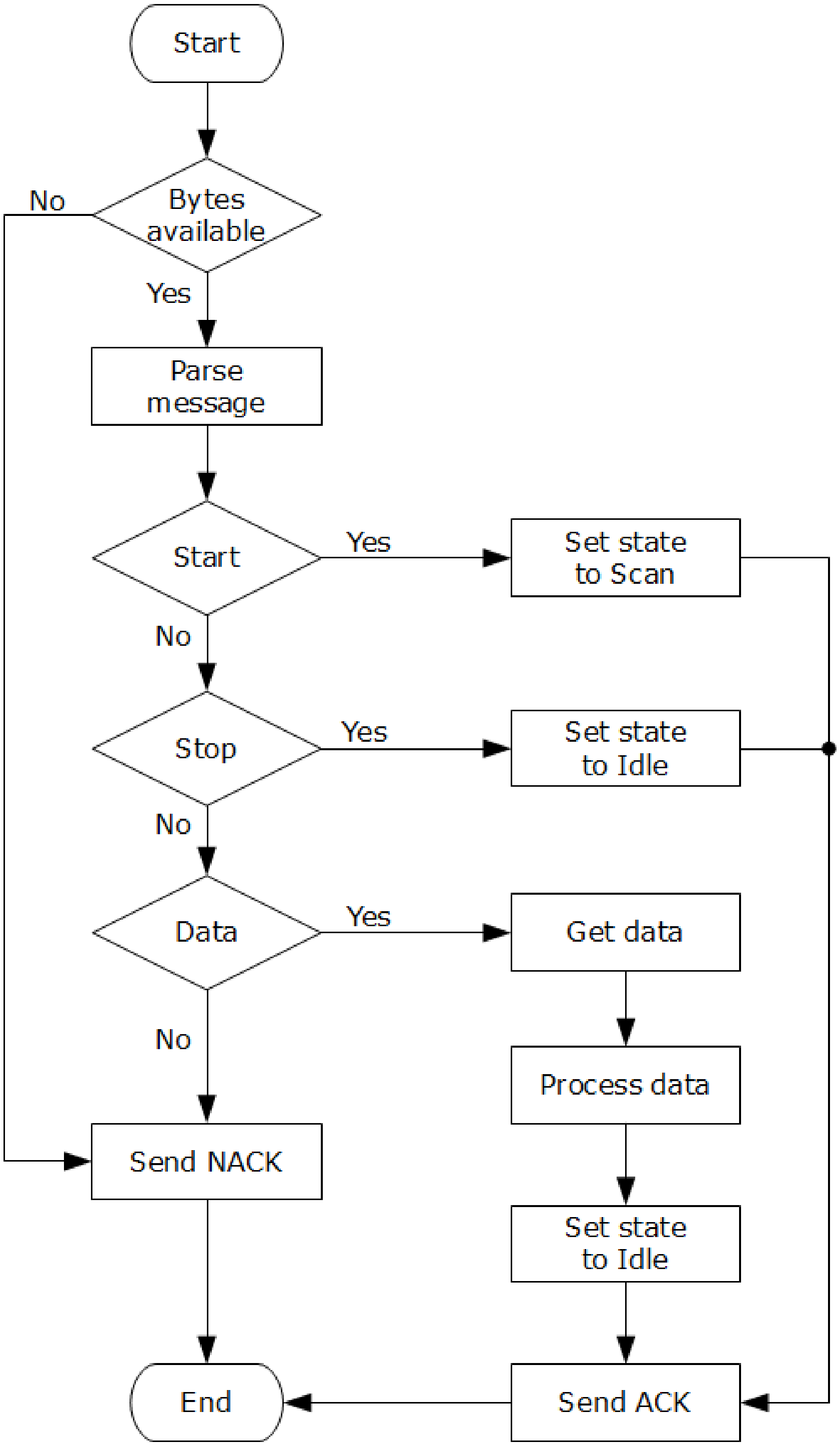


Fig. 3.7 Firmware - communication state algorithm

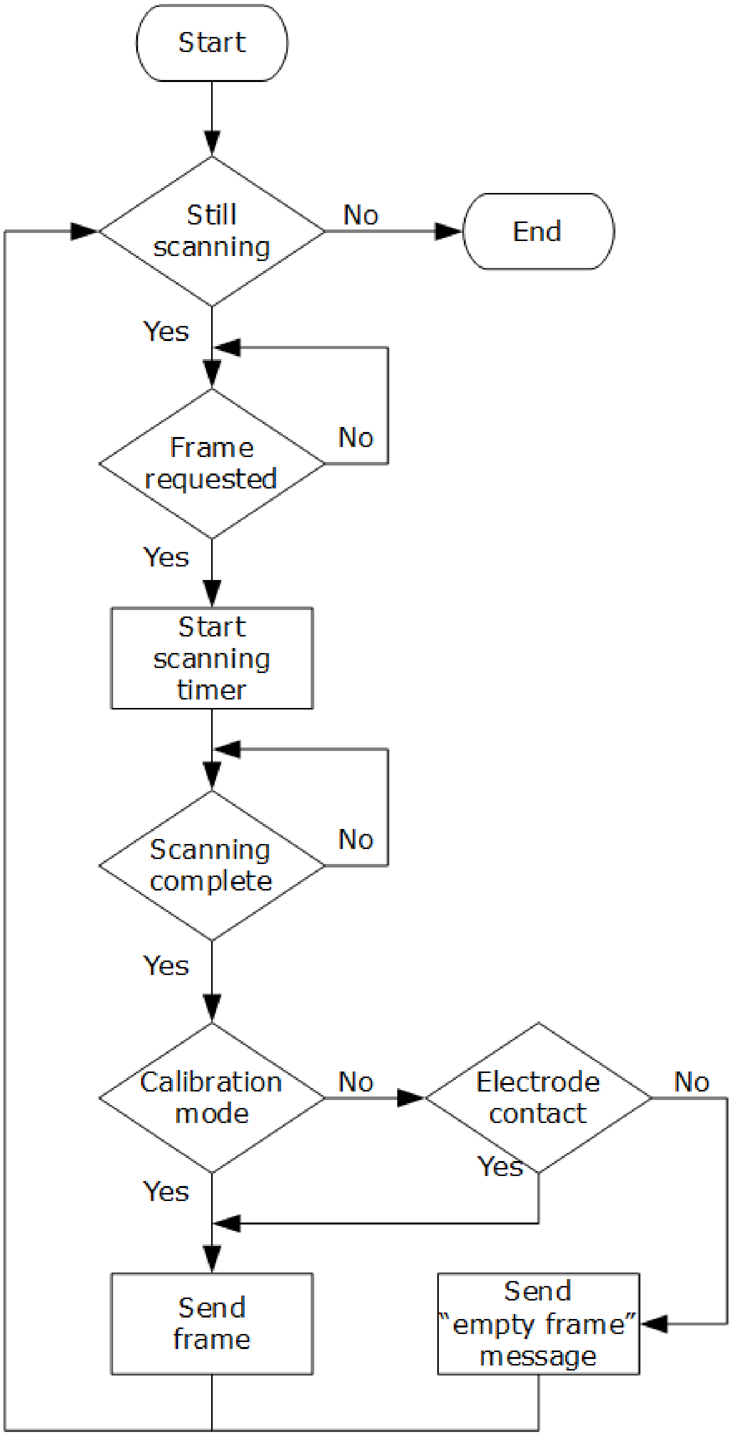


Fig. 3.8 Firmware - scanning state algorithm

During normal use, the contact map is returned only if there is contact, otherwise an "empty frame" message is sent; this is done in order to avoid processing redundant information in the front end.

The back end firmware running on the MCU controls the signal output, and manages the characteristics of the signal, including the frequency. It also handles the addressing of the signal within the switching fabric, and the data acquisition algorithm.

When current is cut off by the safety module, an interrupt is triggered on the MCU. In the ISR, all the ongoing actions are cancelled, the respective timers and flags are reset, and the watchdog timer triggers a system reset.

There are two main types of errors that can occur during the functioning of the device: state machine errors and communication errors. In the case of a state machine error the activity LED (amber) will start blinking at ~5 Hz, the MCU is placed in idle state and the controller will have to be reset to resume operation. For communication errors, like missing bytes or time-outs, the amber LED blinks at ~25 Hz, and operation can co be resumed if a new message is correctly received.

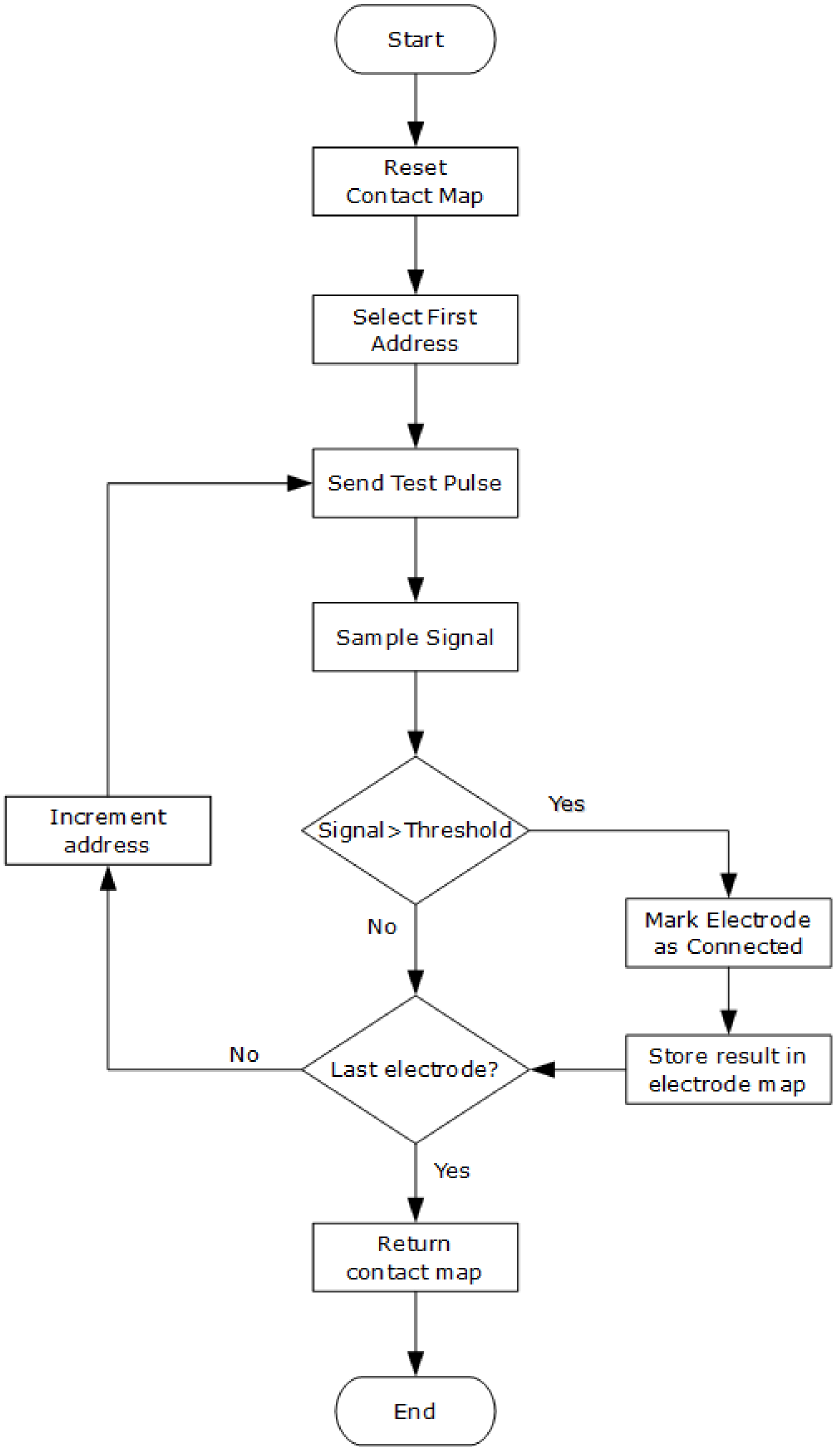


Fig. 3.9 Firmware – electrode scanning algorithm (timer ISR)

3.2.3 The Communication Protocol

A custom synchronous communication protocol was designed to facilitate the wireless communication between the user interface and the controller. The communication is handled via the Bluetooth stack. The MCU communicates with the CS4 BlueCore stack on the Bluetooth module via an UART port, while the GUI is using the BlueCove library to handle the communication (Figure3.10).

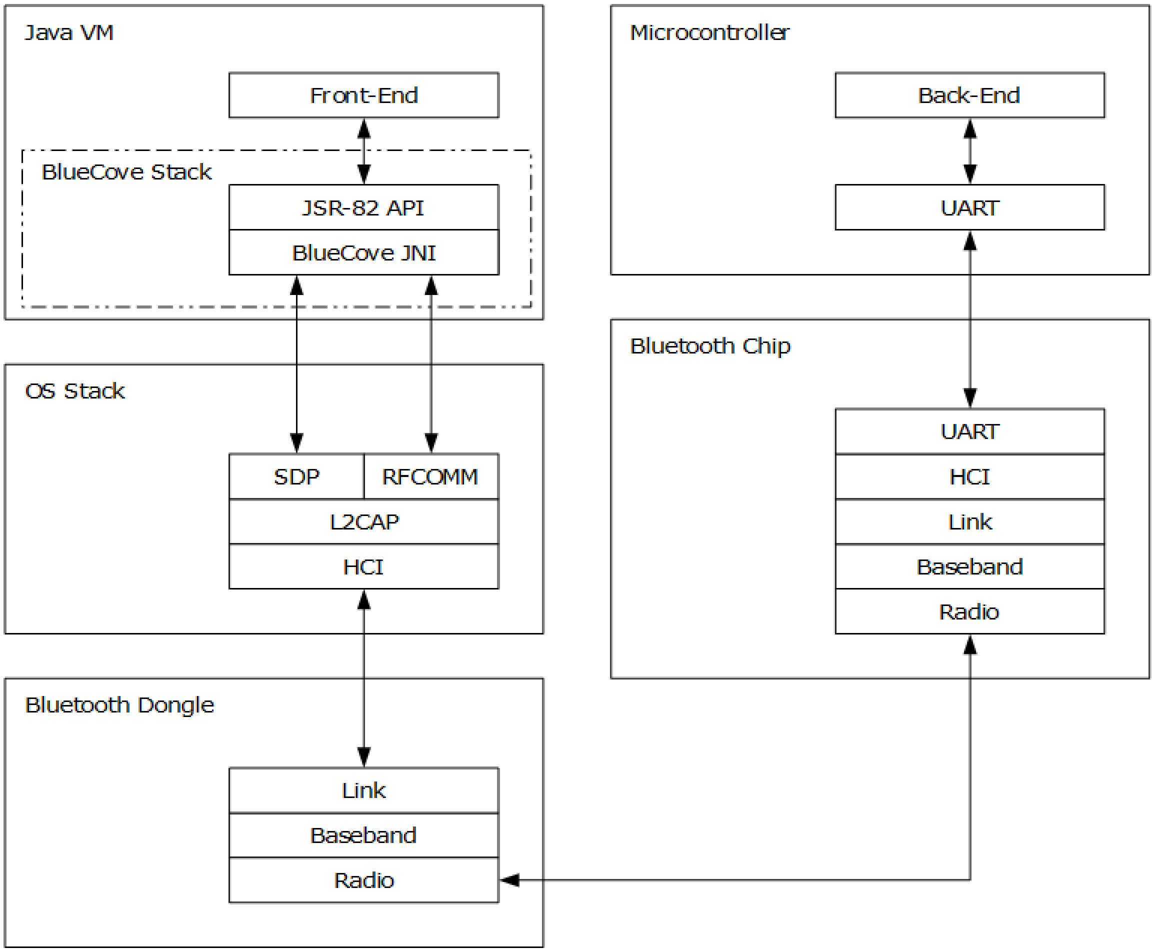


Fig. 3.10 Communication layers – high level view

Master to Slave			
Message	Command	Data	
‘#’	Start	N/A	N/A
‘$’	Stop	N/A	N/A
‘%’	Frame	N/A	N/A
‘/’	Empty Frame	N/A	N/A
‘?’	Test	N/A	N/A
‘+’	Click	N/A	N/A
‘&’	Threshold	Byte 1	Byte 2
‘@’	Amplitude	Byte 1	Byte 2
‘~’	Frequency	Byte 1	Byte 2
‘-’	Duty Cycle	Byte 1	N/A

Table 3.1 Communication protocol: master messages

The presence of an UART serial port on both the controller unit and the Bluetooth chip, and the relative simplicity of the communication process, led to the design of a custom point-to-point asynchronous communication protocol. The serial communication between the controller unit and the host computer is byte-oriented, half-duplex, and has a master/slave configuration.

Slave to Master			
Message	Command	Data	
‘!’	NACK	N/A	N/A
'*'	ACK	N/A	N/A

Table 3.2 Communication protocol: slave messages

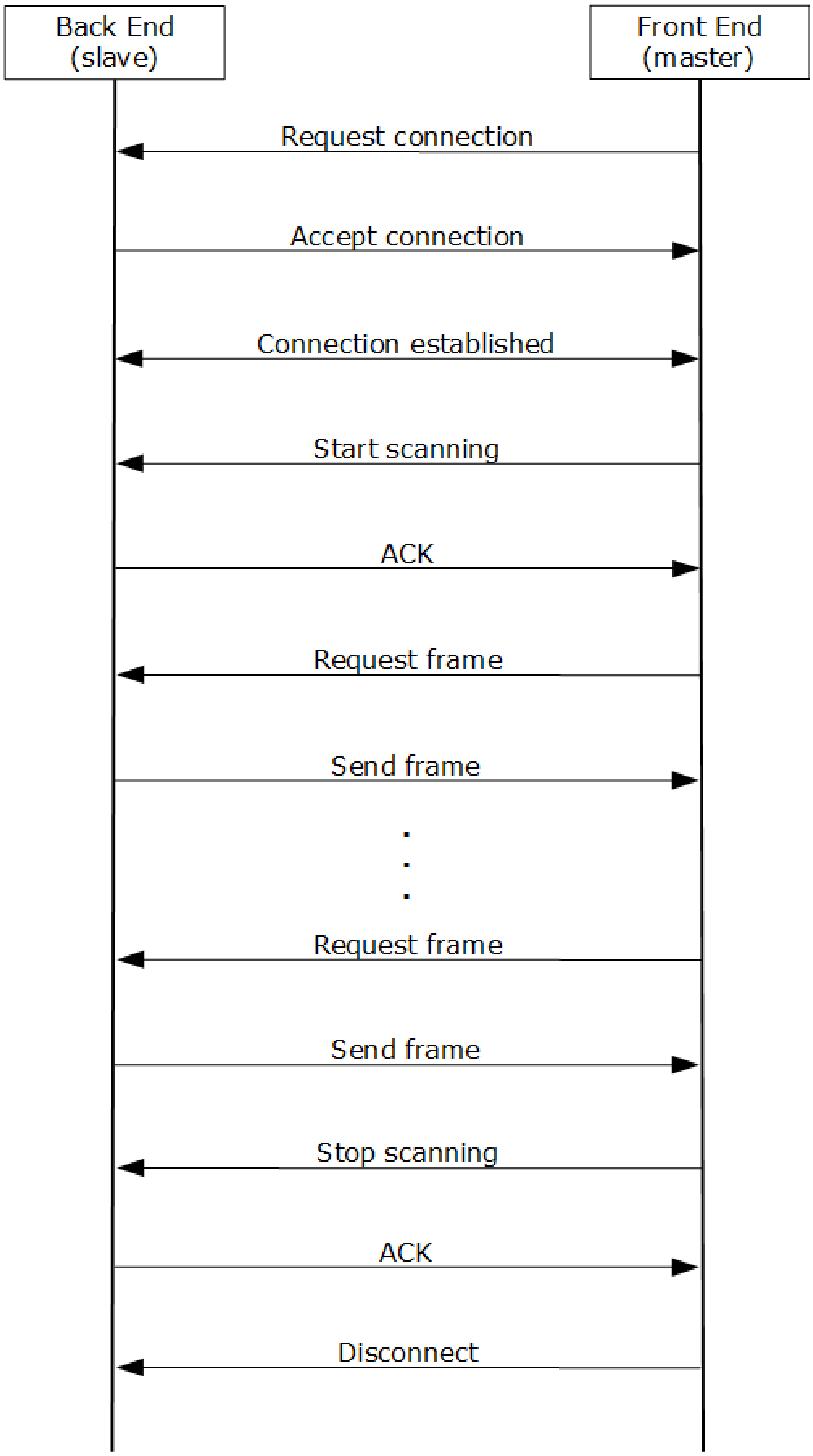


Fig. 3.11 Communication protocol – successful session

The front end software acts always as the master device, controlling the communication with the back end firmware. On the MCU side, the serial communication is managed with the help of a double circular buffer, in a FIFO configuration.

Error checking and 128-bit encryption are implemented in the lower level of the embedded BlueCore stack; therefore they are not addressed in the application layer. The command format and supported commands are listed in Tables3.1 and 3.2.An example of a successful communication session is shown in Figure3.11.

Chapter 4

Applications

4.1 Electrical Stimulation

The system was designed to be capable of providing multiple types of intraoral and transcranial electrical stimulation, both anodal and cathodal, employing alternating or direct current. Intraoral electrical stimulation can be used for sensory substitution [16, 45], as well as for cranial nerve non-invasive neuromodulation (CN-NINM) [10, 11]. Transcranial electrical stimulation is known to induce neuromodulation via various methods, like Transcranial Direct Current Stimulation (tDCS) [46, 47], Transcranial Alternating Current Stimulation (tACS) [48, 49], and Transcranial Random Noise Stimulation (tRNS) [14, 50]; all these methods can be implemented on this system.

There are two types of electrodes that the system can be fitted with: intraoral, and transcranial. Both electrode types can be used for stimulation, as well as impedance measurements.

A pair of anodal and cathodal transcranial electrodes used in tDCS is shown in Figure4.1; these are carbon-rubber electrodes that do not suffer electrochemical polarization at the skin-electrode interface [44].

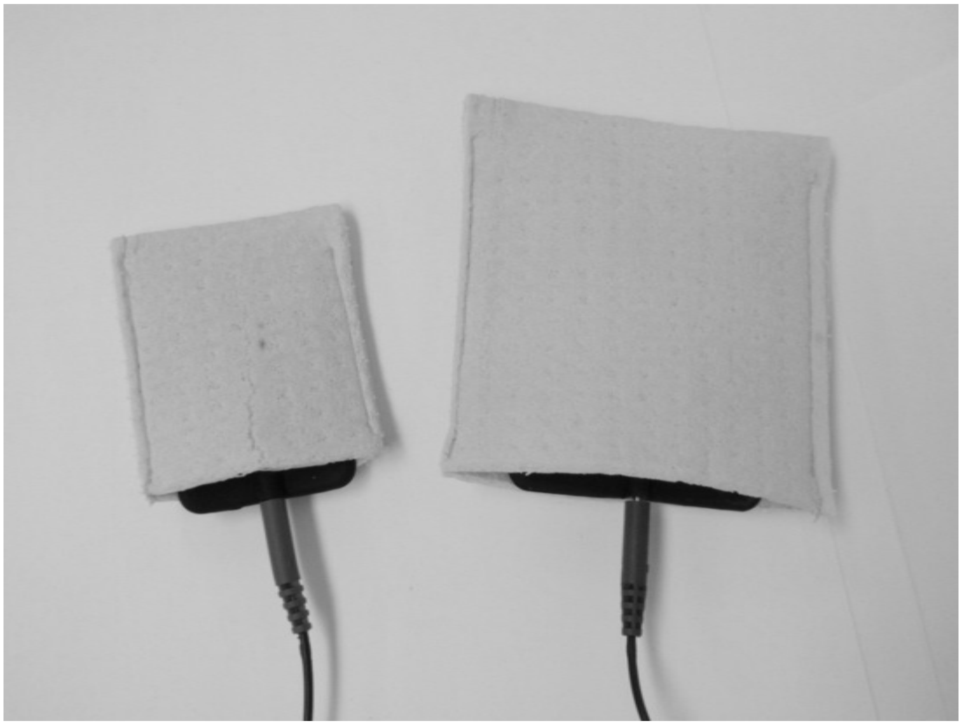


Fig. 4.1 Transcranial electrodes (for tDCS)

4.2 Biofeedback Collection

In the context of this research project, biofeedback collection refers to bioimpedance measurements. For the purposes of the MouthPad application, only tongue bioimpedance information was collected; hence the only pathway used was the intraoral one. Bioimpedance measurements can detect changes in tissue [3], and therefore they can be used in the diagnosis of medical condition. Impedance can also be used to detect the contact between two surfaces, which is the method used in electropalatography [51], as well as in the implementation of the main application of the system presented here.

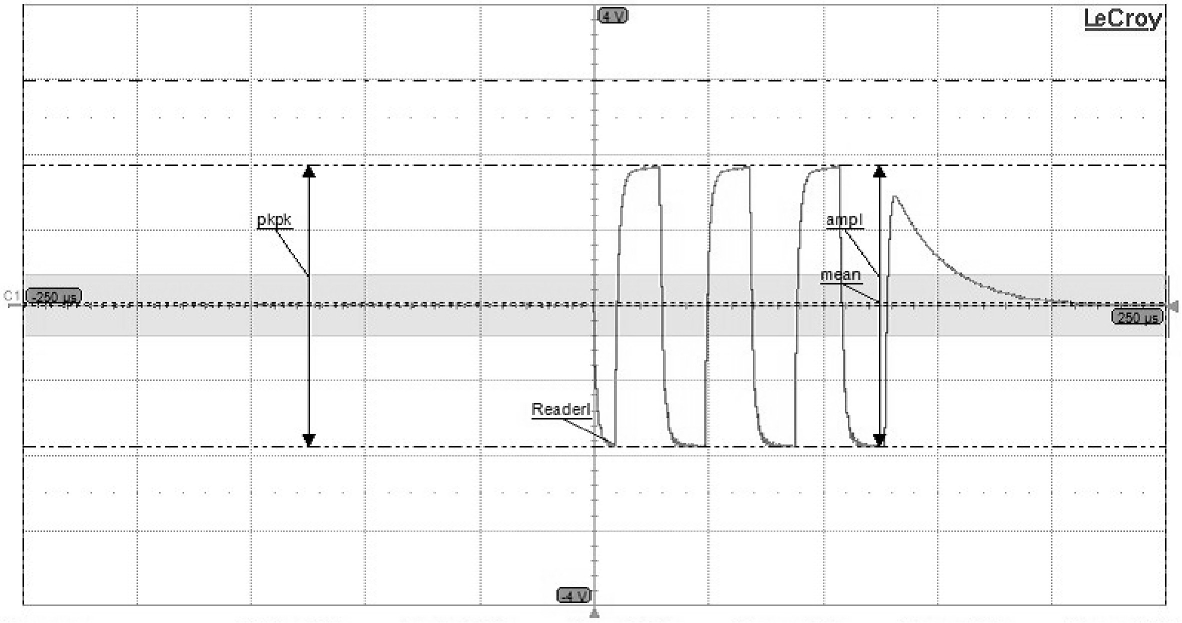


Fig. 4.2 Output - sequence of pulses sent through an electrode

The impedance information is collected by generating an output signal (Figure4.2) through an electrode placed on the body, and measuring the voltage on the return electrode, placed at another location on the body. The signal received through the return electrode is buffered, rectified (Figure4.3), and filtered prior to sampling (Figure4.4). The signal is then sampled through the analog-to-digital converter, and the resulting value is deducted from the amplitude of the output voltage, to obtain the voltage drop caused by the impedance of the tissue.

There are a few methods suggested for the accurate measurement of bioimpedance in a two lead setup [52]. One of these methods is suitable for implementation in this case: the frequency variation technique. The resistance errors caused by electrode polarization are generally smaller than those in capacitance. Capacitance errors are larger at lower frequencies; therefore measurements at lower frequencies determine the values of the polarization capacitance.

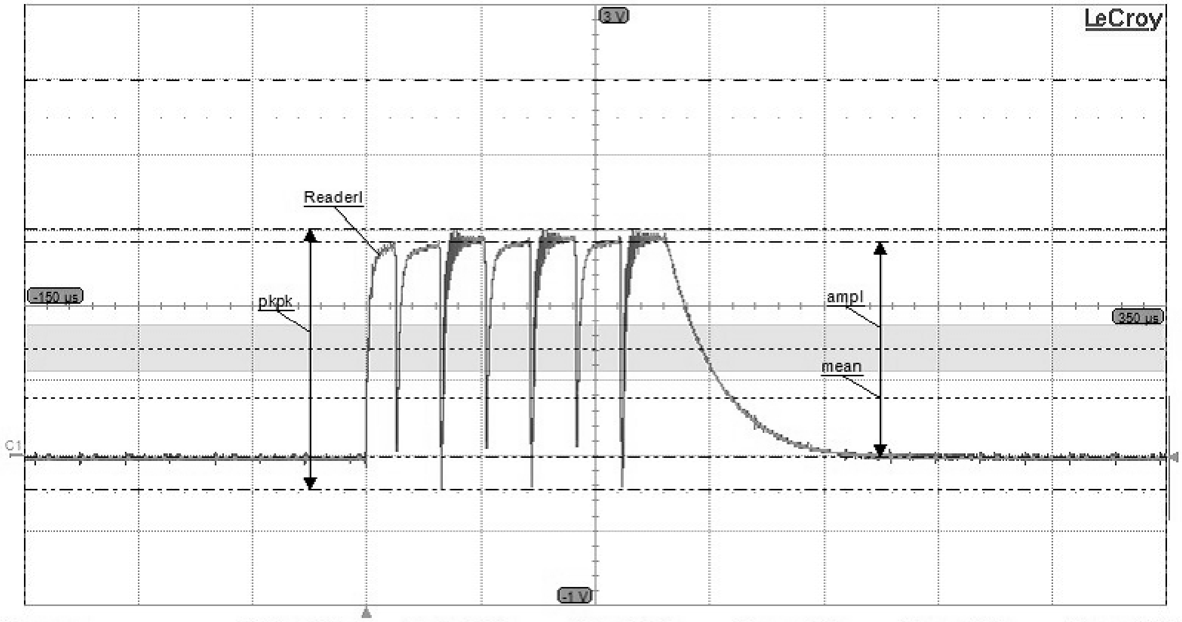


Fig. 4.3 Return signal - rectified

The measurement of impedance has not been applied in this research, since the main application implemented on this system does not require the precise calculation of bioimpedance, but merely the detection of contact between two surfaces; it is the contact between the tongue and the electrode array that matters in this application.

Collecting the biofeedback is done through metallic electrodes, which are known to suffer electrode polarization, and cause tissue electrolysis. Electrode polarization is known to affect impedance measurements in biological tissue [52]. It is known [53] that for platinum electrodes with area larger than 1 mm^2, at frequencies of over 10 kHz, the polarization resistance drops under 10 Ω, and the polarization capacitance under 2 µF. Platinum and gold electrodes have similar behaviour [54], but gold exhibits three times lower polarization at frequencies over 1 kHz.

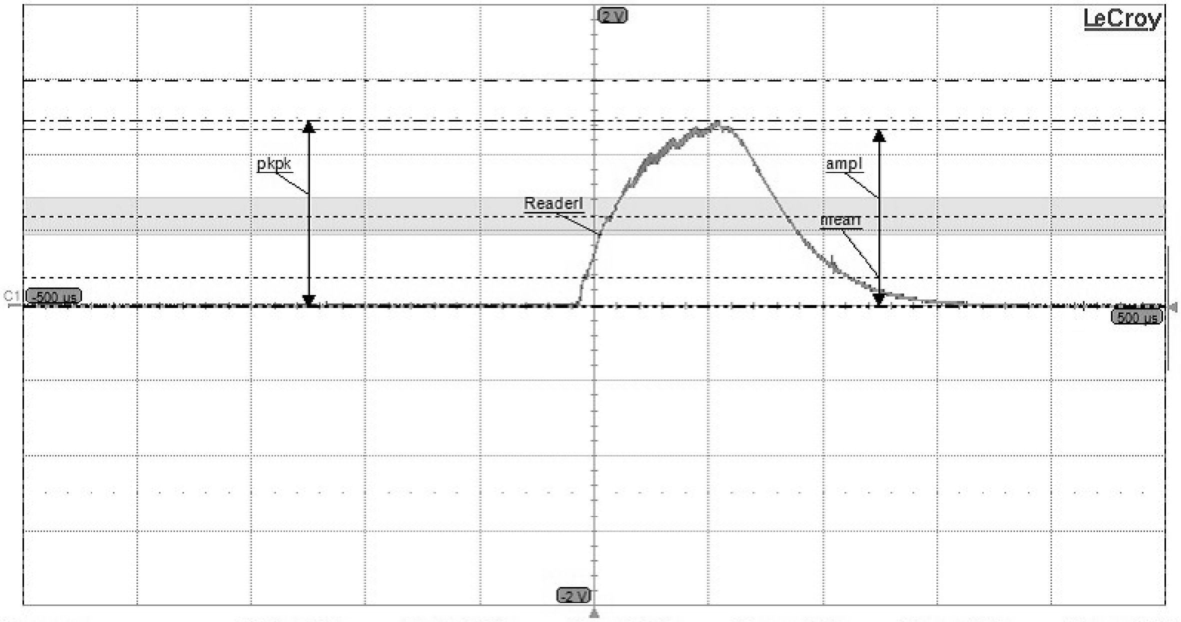


Fig. 4.4 Return signal – filtered

Tissue electrolysis causes electrode material dissolution into the tissue surrounding the electrode, potentially damaging the tissue [55]. To minimize the risk of electrode dissolution [56] the signal used has to be a charge balanced waveform: the charge corresponding to the negative cycle has to be equal to the charge corresponding to the positive cycle.

Therefore, the output signal was selected to be a symmetrical biphasic square pulse, such that the DC component, the electrode polarization effects, and the dissolution of electrode material into the tissue are minimized [57, 58]. The frequency of the pulse is was 25 kHz, which is the highest frequency that the system can generate while maintaining a charge balanced wave; for frequencies closer to 50 kHz, the signal is distorted due to hardware limitations, and the charge balance cannot be guaranteed.

The parameters used in determining the safe levels of current are charge density and current density [59], for AC and DC stimulation, respectively. The charge density per individual electrode for an AC pulse with a 20 μs phase (25 kHz) is ~0.44 C/cm^2 (Equation 4.1).

$$\frac{2\ mA}{20\ \mu s \times 0.225\ cm^2} = 0.44 \frac{C}{cm^2} \tag{4.1}$$

The current density for DC currents is ~8.89 mA/cm^2 (Equation 4.2). Both values are deemed to be well within the levels known to cause tissue damage [59].

$$\frac{2\ mA}{0.225\ cm^2} = 8.89 \frac{mA}{cm^2} \tag{4.2}$$

4.3 Tongue-Computer Interfacing

Interfacing between the system and a human subject can be unidirectional or bidirectional and can employ either electrical simulation alone, or combined with biofeedback collection.

Some of the applications of the tongue-computer interface are hands-free computer control, sensory augmentation and sensory substitution. In the case of computer control, the tongue is used in lieu of the hand or eye gaze in manipulating a mouse pointer or cursor, or the keyboard.

For sensory substitution and augmentation, the tongue device is used as an input device, to provide information to the user. The information can consist of information about the surrounding environment [16], or feedback about the position of the body [6]. Patterns and images are projected onto the tongue using the electrode array. Pattern perception via the electrical current actuated onto the tongue is done in a similar way to reading in Braille with the finger tips.

Two applications have been implemented on the system presented here. The main application, the MouthPad, involves hands-free computer control, and employs bioimpedance measurements. The second one deals with pattern recognition via electrical stimulation, more specifically alphanumeric character recognition.

Chapter 5

Implementations

5.1 Computer Control

The first application developed on this system, and the subject of this thesis, is a tongue-computer interface that allows the user to control a computer hands-free. The mouse pointer of the controlled computer is manipulated through the movement of tongue on the electrode array, in the same manner as with a regular joystick.

5.1.1 Interface Implementation

The method used to implement this interface is the measurement of the amount of voltage allowed through the return electrode by the contact between the tongue and the electrode array. The voltage measurement is used to detect the degree of contact between the tongue and the tongue device, which in turn is used to monitor in real time the position of the tongue, and consequently its movement over the electrode array.

A sequence of symmetrical biphasic square pulses is sent through an electrode. When the electrode array is touched by the tongue, the current is allowed to close through the return electrode connected to the body of the subject, either intraorally or transcutaneously; then the voltage is sampled on the return electrode by the built-in ADC.

The address of the electrode through which the signal is outputted is known at the time of the A/D conversion, making it is possible to map the contact between the tongue and the electrode array. If the voltage sampled is higher than a set threshold, the electrode is deemed to be in contact state. The state of the electrode is stored into a contact map.

The electrodes used for outputting signal and are referred to as "active". The cycle of generating and sampling the signal on one electrode is performed sequentially for the entire set of active electrodes, and is referred to as “scanning”. The full scanning cycle produces a contact map, referred to as a "frame". The resulting frame is send to the controlled computer.

The amplitude of the voltage was limited to a minimum 2 V and maximum 6 V. It was determined experimentally that under 2 V it becomes difficult to detect tongue movements accurately, since the level of the return signal drops too low to allow good resolution for the contact map. Over 6 V most of the users have reported noticing the signal and feeling discomfort.

The involuntary movements of the tongue, and the need to control the amount of pressure applied by the tongue onto the electrode array, rendered the return electrodes on the tongue device unusable. As a consequence, the return was connected to the wrist of the right hand, using a transcutaneous polymer electrode of the ECG type with gel adhesive. The intraoral return electrodes could be used if the tongue device would embedded into a palatal retainer.

5.1.2 Movement Control

Of the 49 intraoral electrodes on the tongue device, only 16 are used in the joystick mode (Figure5.1). The number and the location of the electrodes used for the joystick function were selected experimentally, by taking into consideration the shape of the tongue, and the tongue's natural movement patterns.

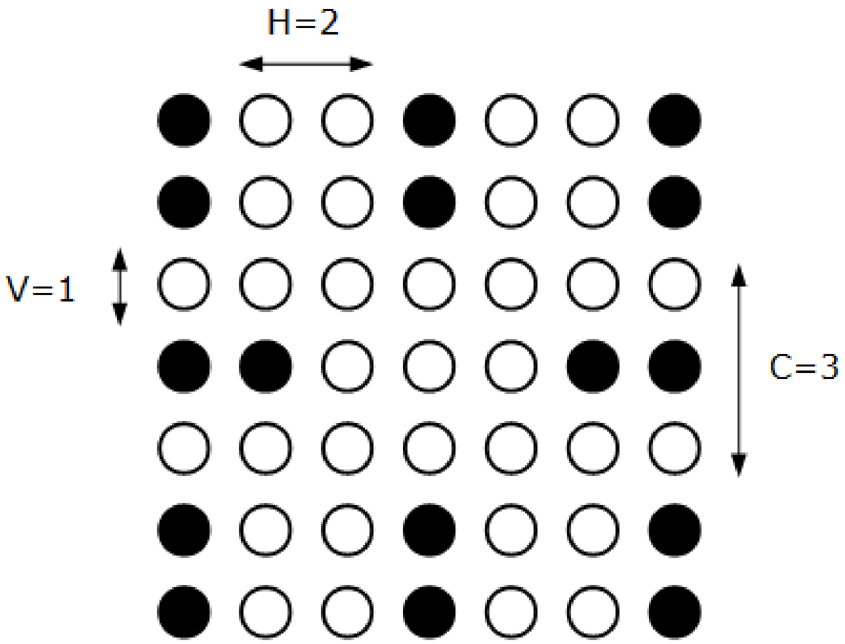


Fig. 5.1 Electrode scanned in joystick mode (in black) and gap sizes

Due to the oval shape of the tongue's tip, the vertical gaps (V in Figure5.2) have to be larger than the horizontal ones (H in Figure5.2). The central gap has to be large enough so that the tongue cannot touch opposing electrodes simultaneously, since this would cause the pointer to move into the wrong direction.

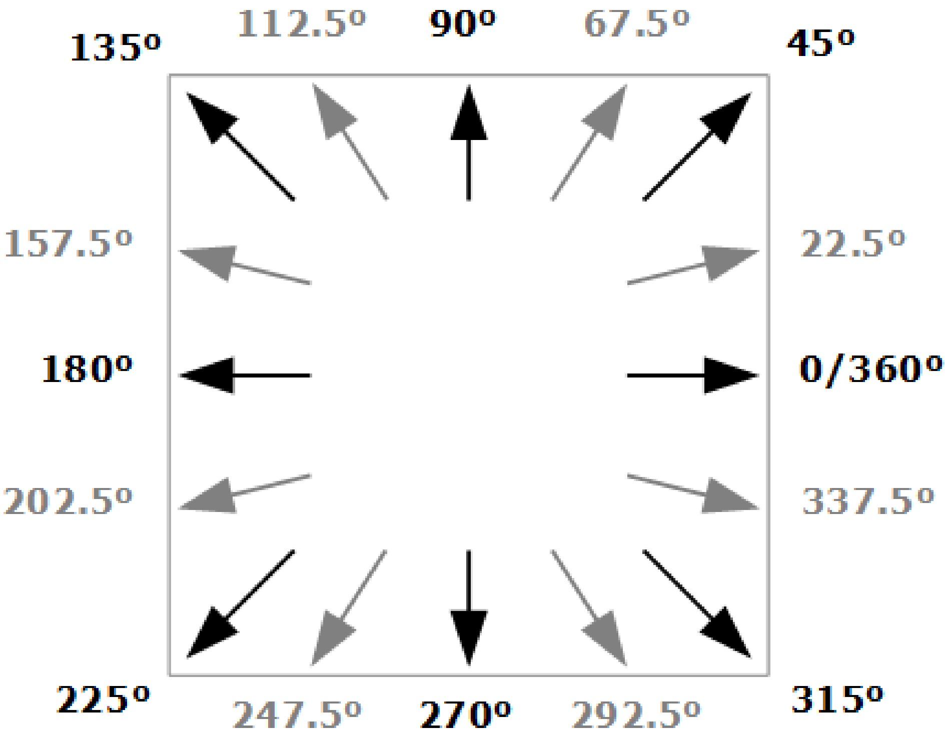


Fig. 5.2 Pointer directions (main in black and intermediate in gray)

There are eight main directions of movement, represented by eight pairs of electrodes. These electrode pairs are referred to as a "switches", since they act as direction switches in joystick mode. Another eight intermediate directions are calculated at run time as following: if the tongue touches electrodes in more than one main direction group, then the direction is taken as the average of the respective main directions (Figure 5.2).

Involuntary tongue moves (e.g. swallowing); can cause the tongue to come in contact simultaneously with too many electrodes, resulting in a random direction change of the cursor. To avoid this kind of situation, a limit was set for the number of electrodes in contact allowed within a frame. If this limit is reached, the frame is deemed invalid, and no cursor move is triggered.

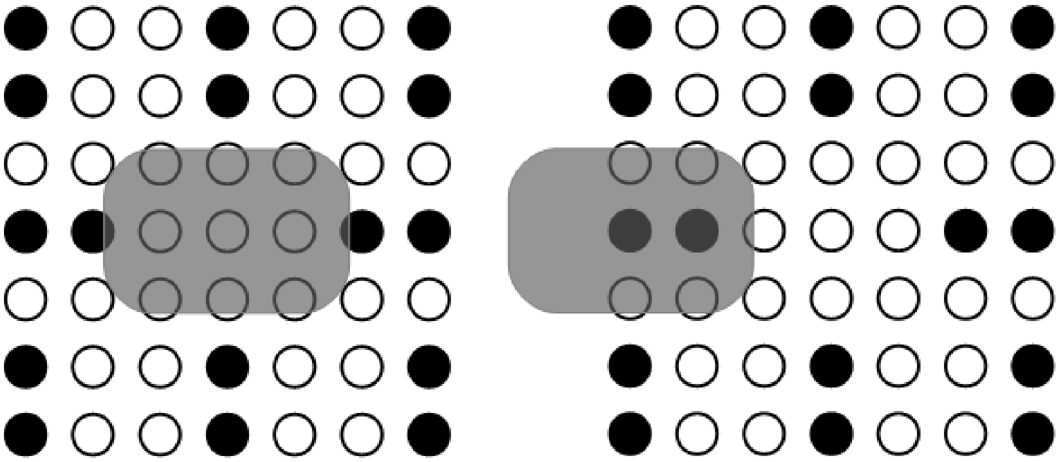


Fig. 5.3 Directions: neutral, and main (180º)

At the rate of about 25 frames per second, the movement of the pointer on the screen is rather slow. To compensate for the slow pointer speed, acceleration was implemented in the front-end software application.

The actuation of the mouse pointer through tongue contact mapping is shown in Figures 5.3, 5.4, and 5.5. The main directions are taken by touching one single switch with the tip of the tongue. For the intermediary directions, the tongue has to touch two adjacent electrode switches.

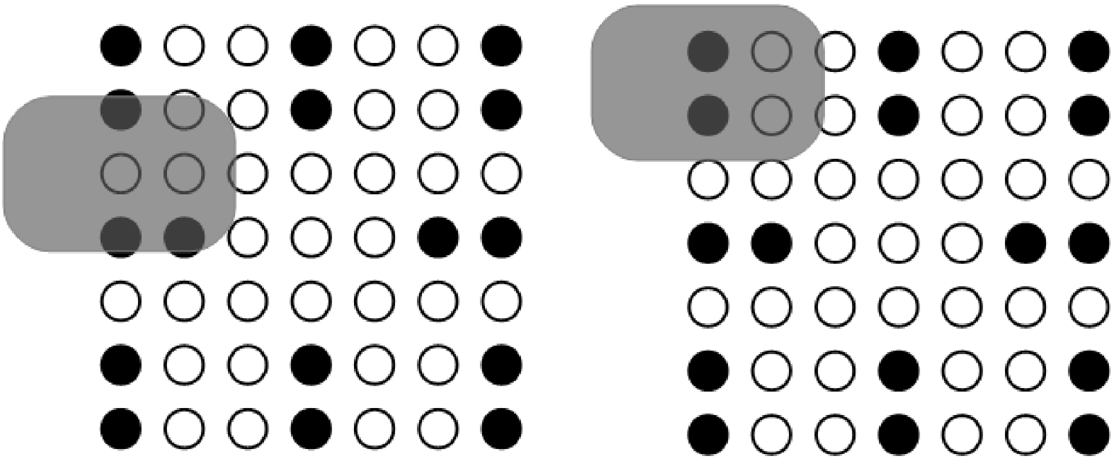


Fig. 5.4 Directions: intermediary (157.5º), and main (135º)

The mouse click was not implemented in this version, due to lack of dedicated electrodes on the tongue device. The space bar and the left button of laptop’s touchpad were used to emulate the clicks.

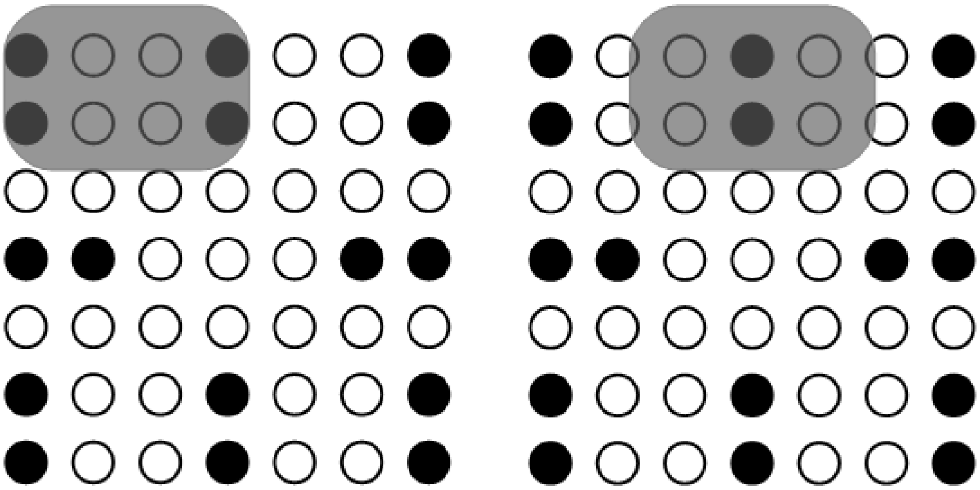


Fig. 5.5 Directions: intermediary (112.5º), and main (90º)

5.1.3 System Calibration

The calibration is performed at the beginning of a user session, as well as during the usage, as needed. All the electrodes in the intraoral array are used in calibration mode, and provide the user with the size and shape of the tongue's footprint.

The calibration process consists of two steps. The first step involves the adjustment of the output signal’s amplitude, while in the second step the contact threshold is tweaked.

Output Signal

Because this application is oriented towards research and human trials, the adjustment of the voltage level was not implemented in the software, so that it would not be available to the user. The adjustment has to be done by the researcher with the help of a potentiometer on the controller board.

The user starts increasing the voltage from the lowest level, until the presence of the output signal on the tongue becomes noticeable. The voltage amplitude of the output signal is then kept at the same level until the next calibration.

Contact Threshold

The second parameter to be adjusted is the contact threshold for the analog-to-digital converter. The contact threshold for the A/D converter can be set from the GUI, allowing the resolution of the contact map to be adjusted, such that only an optimal number of electrodes are deemed in contact; this allows the user to increase both the responsiveness, and the accuracy of the system.

The system's responsiveness and accuracy are dependent on the resolution of the contact map. As previously described, when too many electrodes are active, no pointer movement is triggered and the frames are skipped, therefore causing a decrease in responsiveness. On the other hand, when not enough electrodes are active, the intermediary directions are virtually impossible to be detected; hence causing a loss of accuracy, since in this case only half of the 16 directions remain available to the user.

For the system to function properly, the size of tongue's contact footprint on the electrode array needs to be kept at an optimal size. This is done by controlling the contact threshold for the signal sampled on the return path. The user can also adjust the size of the tongue's footprint by varying the pressure exerted by the tongue on the electrode array.

Moving the pointer on one of the intermediary directions requires that the tongue makes contact with the two adjacent switches. It is considered acceptable for the tongue to be in contact simultaneously with at most three switches, as the accuracy does not seem to decrease significantly; in such a situation the direction taken is the median one. In joystick mode, the maximum number allowed of electrodes in contact per frame was set to six. This accounts for at most three main directions, since each main direction is represented by one pair of electrodes.

The unused electrodes between the electrode switches are referred to as "gaps". The horizontal, vertical, and the central gaps are of one, two and three electrodes, respectively (Figure5.1).

The user's tongue needs to be able to make contact with two adjacent switches in order to be able to use the intermediary directions. It is also necessary that the tongue footprint does not cover more than the gap plus one electrode, or else the user will not be able to use one main direction only, since the tongue will always make contact with at least two switches in the same time.

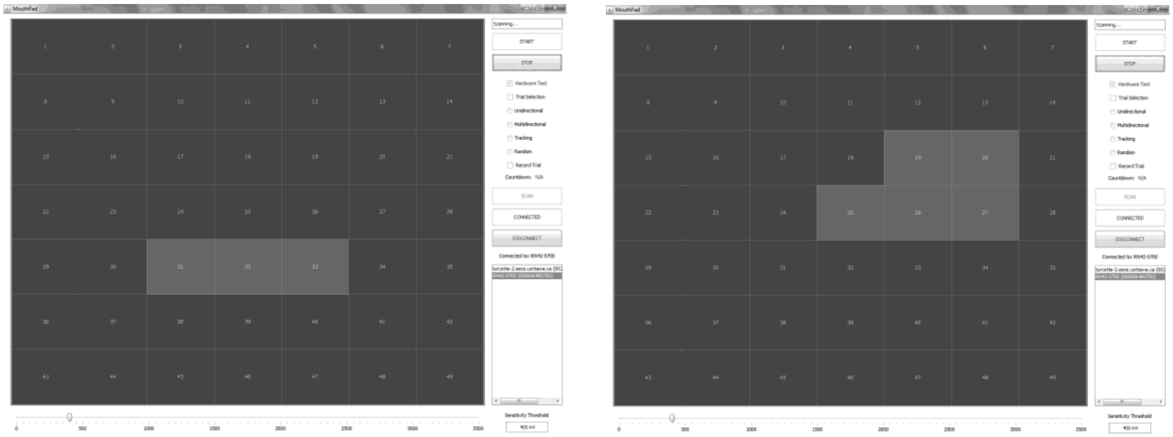


Fig. 5.6 Footprint (400 mV threshold): normal and higher pressure

Considering the placement of the electrode switches on the tongue board, and the size of the gaps, it was determined that the ideal area of contact is a rectangle with a height between two and three electrodes, and a width between three and four electrodes (Figure5.1).

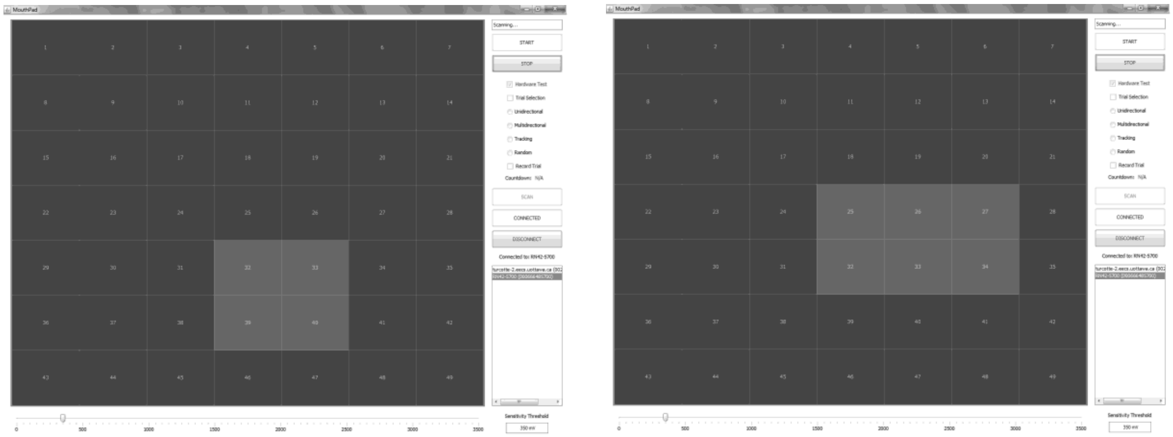


Fig. 5.7 Footprint (350 mV threshold): normal and higher pressure

The variation of tongue's footprint during the calibration is shown in Figures 5.6 to 5.12. The process was started with a 400 mV threshold, and continued by lowering the threshold, in 50 mV decrements, down to 100 mV.

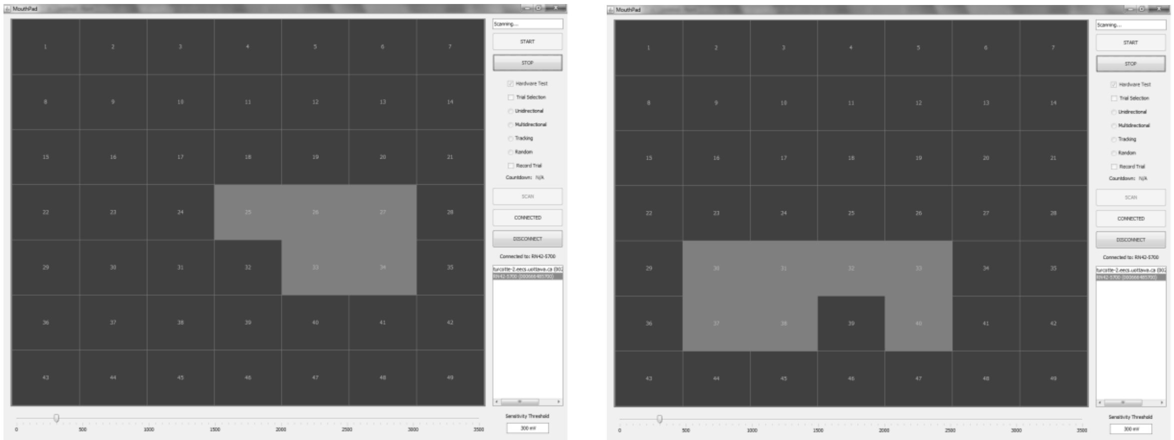


Fig. 5.8 Footprint (300 mV threshold): normal and higher pressure

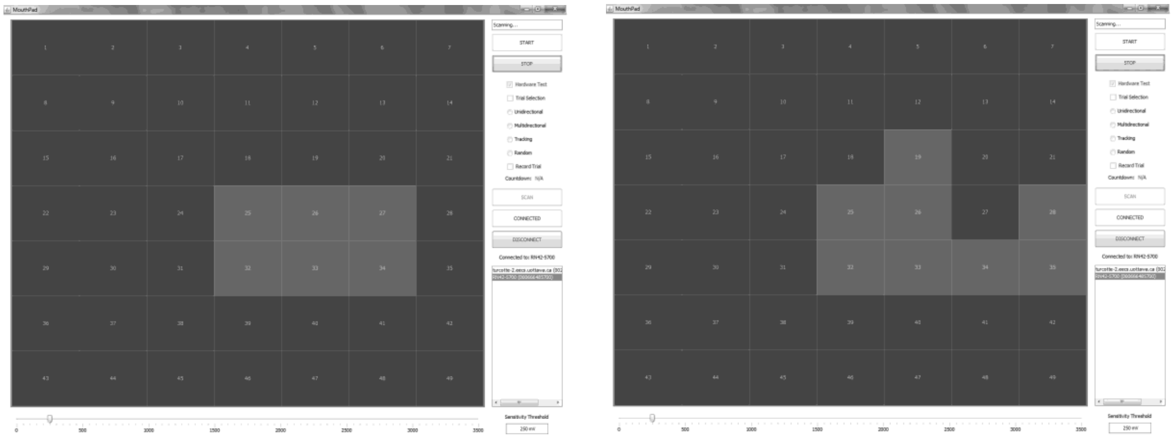


Fig. 5.9 Footprint (250 mV threshold): normal and higher pressure

The calibration is performed with the user exerting higher than normal pressure on the tongue device, which yields a smaller area of contact under normal tongue pressure. This appears to be a disadvantage at the first glance, but it is offset by the secretion of saliva, which enlarges the area of contact over time.

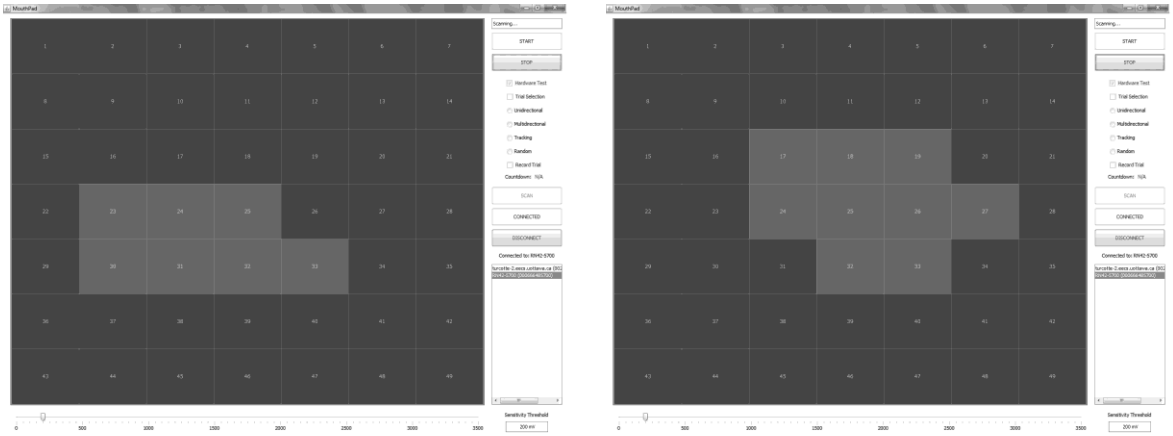
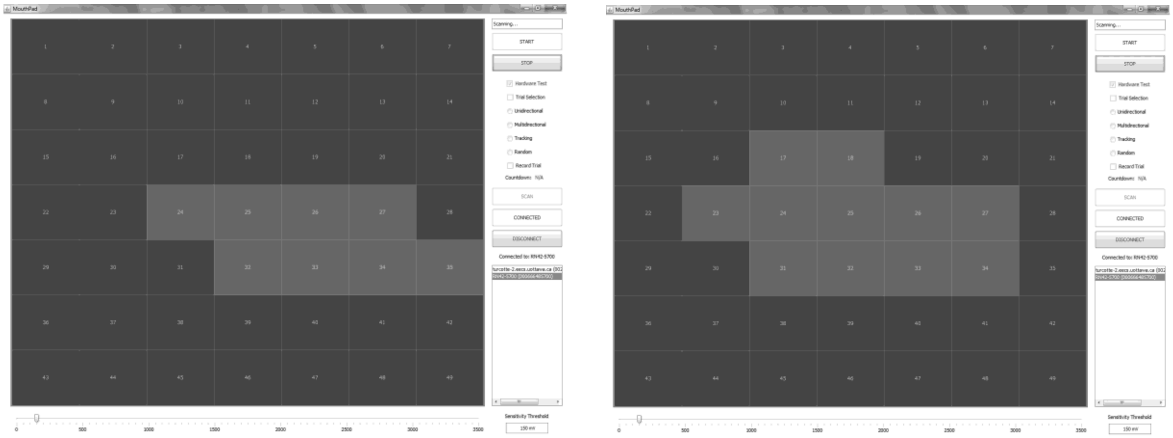


Fig. 5.10 Footprint (200 mV threshold): normal and higher pressure

The optimal range of the threshold was observed to be between 100 and 350 mV, depending on the impedance of the tongue tissue of the respective individual. In the case presented here, the optimal voltage threshold was 150 mV (fig 5.11).



Scanning...

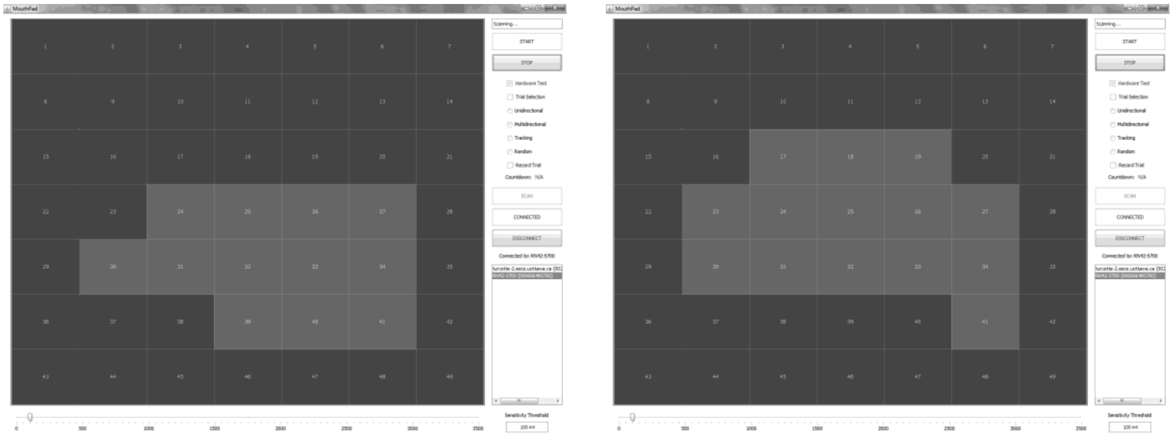
☑ Hardware Test
☐ Trial Selection
○ Unidirectional
○ Multidirectional
○ Tracking
○ Random
☐ Record Trial
Countdown: N/A

Connected to: RN42-5700

Sensitivity Threshold
150 mV

Fig. 5.11 Footprint (150 mV threshold): normal and higher pressure

Further testing is performed in joystick mode: the subject is asked to move the pointer on the screen in all the 16 directions available. If pointer lag is noticed, or the user cannot properly control the direction of the pointer, the threshold is adjusted incrementally, until no noticeable lag is present and the system becomes accurate enough.



Scanning...

☑ Hardware Test
☐ Trial Selection
○ Unidirectional
○ Multidirectional
○ Tracking
○ Random
☐ Record Trial
Countdown: N/A

Connected to: RN42-5700

Sensitivity Threshold
100 mV

Fig. 5.12 Footprint (100 mV threshold): normal and higher pressure

5.2 Pattern Recognition

One of the first experiments performed on this system involved electrical stimulation, and targeted sensory substitution. Patterns were actuated onto the tongue through the electrode array, for the user to recognize.

Initially simple static geometrical shapes were used, similar to what Bach-y-Rita et al. [16] have used: vertical horizontal and diagonal lines, circles, squares, and triangles. Then dynamical patterns were employed, like rotating lines and moving dots.

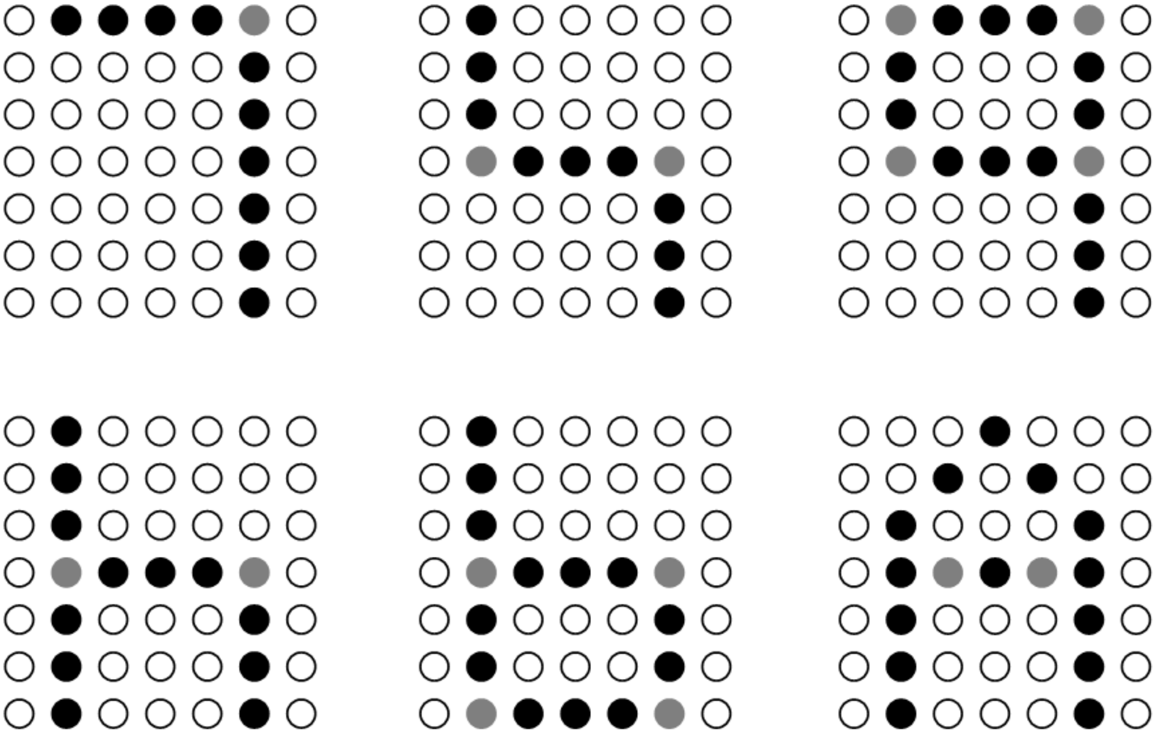


Fig. 5.13 Alphanumerical characters: numbers top, letters bottom

The final tests in this experiment involved the recognition of alphanumerical characters. The characters are displayed in a customized seven-segment display format. Certain characters had to be tweaked to be perceived properly on the tongue. The electrodes located at the intersection of two perpendicular lines are not used (marked amber in Figure5.13), since spatial summation [60] can occur, and alter the perception of the respective pattern.

The front-end was implemented in Java on an Android (version 2.1) smartphone (Acer Liquid E), which connected to the controller unit via Bluetooth. The patterns and the characters were selected by another person who handled the smartphone. A time delay was interposed between commands, to allow user of the tongue device time to recognize the respective pattern.

Despite being relatively successful, the results of the previously described experiments are not presented in this thesis, since they were performed on an early design prototype of the system, implemented in collaboration with other students, and their intended application is not part of the subject of this thesis.

Chapter 6

Preliminary Testing

6.1 The Tongue Phantom

Preliminary experiments were performed on a tongue phantom, in order to investigate the use of the bioimpedance measurements for the monitoring of the tongue's movement. Play-Doh® was used to build the tongue phantom. An Agilent 33220A function generator was used to generate the test signals, while the frequency and the voltage measurements were recorded with a LeCroy waveRunner 64Xi oscilloscope.

A biphasic square wave signal, with amplitude of $^{+}/_{-}$ 2.5 V, was sent through one of the electrodes (electrode 25 at row 4, and column 4). The frequency of the signal varied from 1 kHz to 1 MHz, on a logarithmic scale. The variation of the voltage with the frequency of the signal, for the phantom tongue, is shown in Figure6.1. The most important drop in the signal's voltage (0.55 V or 22 %) has been observed at 50, 100, 200, and 500 kHz.

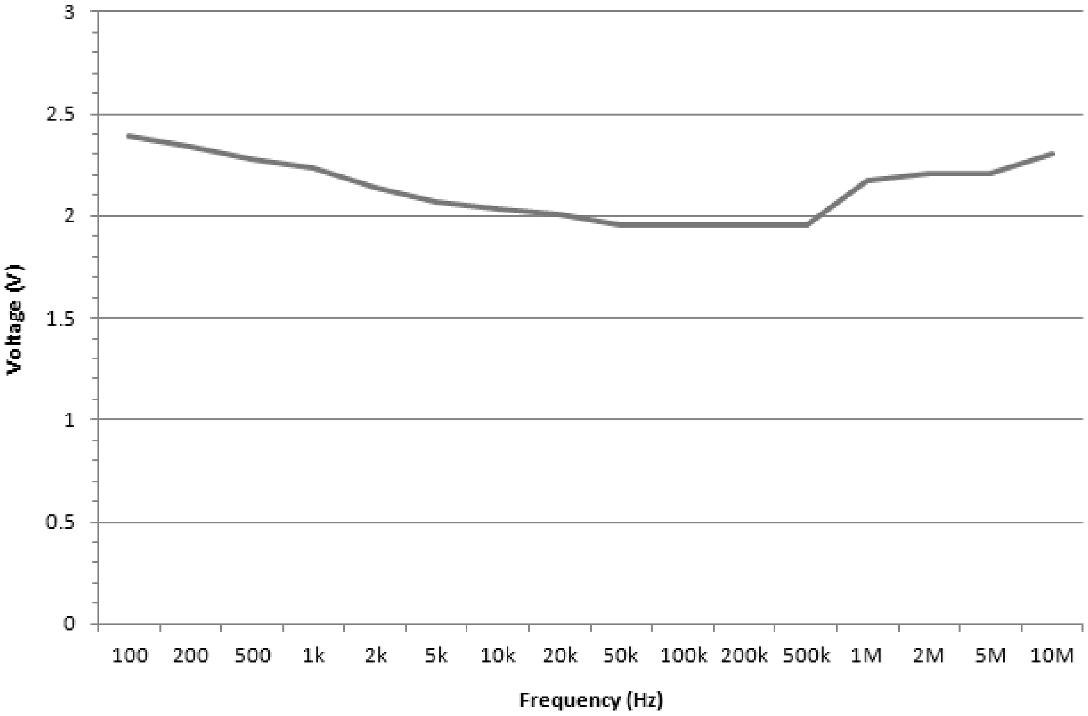


Fig. 6.1 The variation of the impedance with the frequency of the signal

A differential measurement [52] in a voltage divider was used to measure the impedance of the Play-Doh® phantom. The same square wave, with the frequency set at 50 kHz, was sent through the circuit, and the voltage drop measured with the phantom added in parallel to one of the known resistors was used to determine the impedance. The phantom's impedance was measured at around 100 Ω. The variation of the phantom's impedance with the frequency of the signal is similar to what Sun et al. [3] have previously observed; they have found the impedance of healthy tongue tissue to be around 500 Ω at 50 kHz. The use of the Play-Doh® as human tissue phantom [61], coupled with the results of the experiments, led to the conclusion that a Play-Doh® tongue phantom was a good option for the preliminary tests.

6.2 Contact Detection

A piece of phantom tissue was placed over the tongue device, making contact with six of the electrodes in the array. A sequence of biphasic square pulses, of $^+/_-$ 2.5 V amplitude, was applied on each of the respective electrodes. The frequency of the signal was set to 50 kHz, such that the AC induced electrode polarization resistance would be minimal.

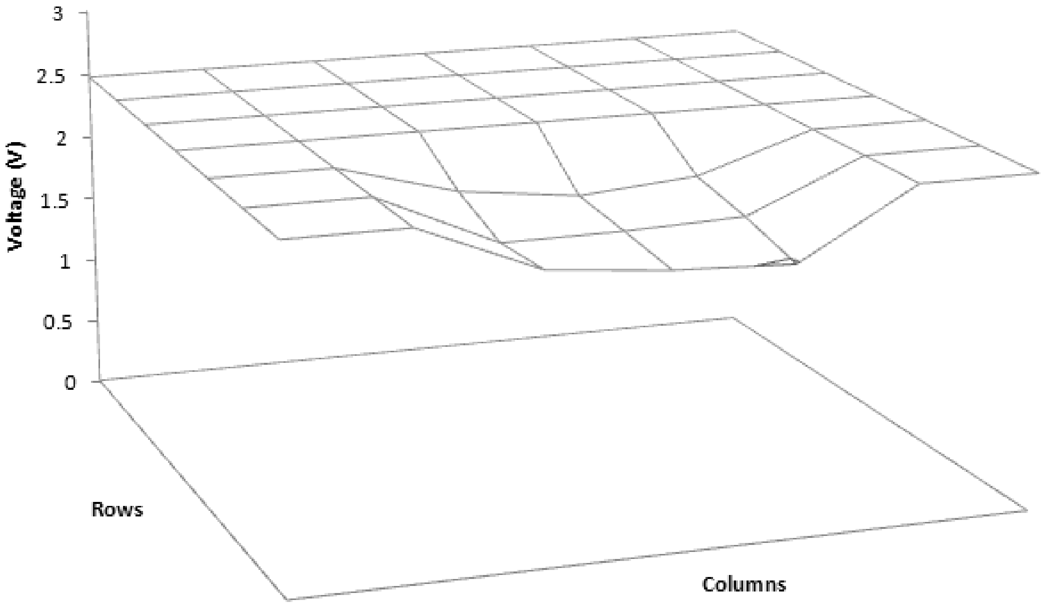


Fig. 6.2 The contact map of the electrode array

The voltage was measured on the output electrode with the oscilloscope. The region of contact between the phantom and the electrode array is shown in Figure6.2. Since on the test rig the measurements were performed on the source, it was a voltage drop that was measured, and that signalled a contact between the electrode and the phantom. On the system itself, the measurements are performed on the sink (i.e. return electrode); therefore the system measures a voltage rise from ~0 V, rather than a drop, for the detection of the contact.

Chapter 7

Performance Evaluation

For the evaluation of this system, a standardized test was chosen, as outlined in part 9 of the ISO 9241 standard. The ISO 9241 standard describes the ergonomic requirements for human-computer interaction. Part 9 of ISO 9241 covers the requirements for non-keyboard input devices, and establishes test procedures and evaluation guidelines for computer pointing devices.

7.1 Parameters

One single performance measure, the throughput (TP), is laid out in the ISO 9241-9 standard. Both speed and accuracy are incorporated in the throughput, which is based on Fitts' index of performance (IP) [62], and is measured in bits/second.

$$IP = \frac{ID}{MT} \tag{7.1}$$

The movement time (MT) is measured in seconds, and represents its reciprocal parameter, the speed of the motor task. ID, expressed in bits, is the index of difficulty of the respective task; W is the width of the target, while D represents the distance to the target.

$$ID = log_2 \left(\frac{D}{W} + 1 \right) \tag{7.2}$$

Shannon's formulation of the index of difficulty, called the effective index of difficulty (ID_e), was used to calculate the throughput of the system, based on the recommendation of Soukoreff and MacKenzie [62].

$$TP = \frac{ID_e}{MT} \tag{7.3}$$

For the Fitts' law to be applicable in the evaluation of motor tasks a Gaussian distribution of selections is assumed, therefore the target width is normalized resulting in the effective target width (W_e).

$$ID_e = log_2 \left(\frac{D}{W_e} + 1 \right) \tag{7.4}$$

The end point scatter is accounted for by using the effective width, rather than the actual width of the target; this allows the measurements to be adjusted for accuracy [62]. When normalizing the target width, the results represents what the subject actually does, rather than what was expected to do [63].

$$W_e = 4.133\, \sigma \tag{7.5}$$

The standard deviation (σ) of the end point coordinates was multiplied with 4.133 to obtain the effective width, as indicated by MacKenzie [63].

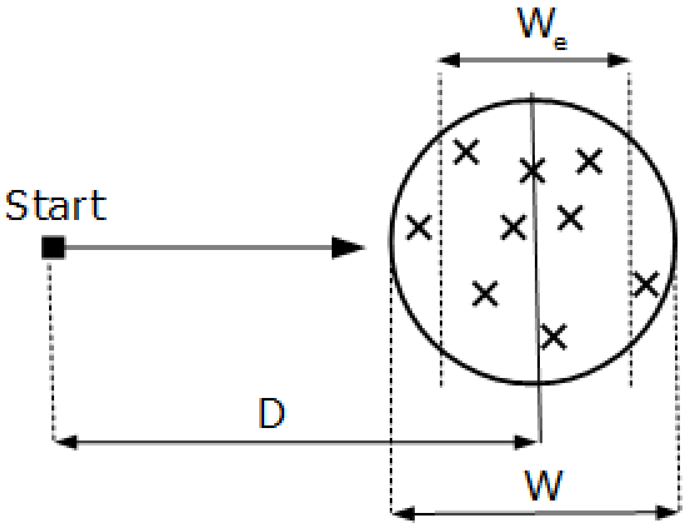


Fig. 7.1 End point scatter

The end point scatter is the distance from the selection point to the axis of the target (z in Figure7.2), and was measured on the straight line from the starting point to the center of the target.

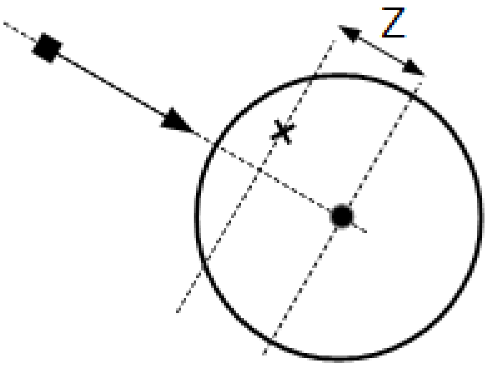


Fig. 7.2 Distance from the selection point to the axis of the target

The error rate was measured as a percentage of missed target selections (clicks outside the target area), and represents the accuracy.

MacKenzie, Kauppinen, and Silferberg [64] have proposed seven new accuracy measures for the testing of pointing devices. Two of these measures were observed by the authors to weigh more than all the others in the prediction of the throughput. The measures were the movement offset (MO), and the target re-entry (TRE); together they amounted to 61 % of the throughput's variance.

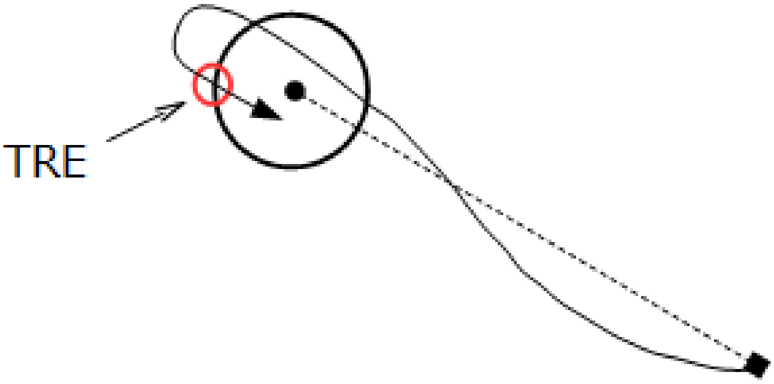


Fig. 7.3 Target re-entry

TRE occurs if the pointer crosses the target, no selection being made, and then returns over the target. A target re-entry is depicted in Figure7.3. Target re-entries are reported per selection; three target re-entries over ten selections result in a rate of 0.3 TRE per selection.

The mean deviation of the pointer from the ideal trajectory represents the movement offset (Figure 7.4). In this case, the ideal trajectory is the straight line between the starting point and the center of the target.

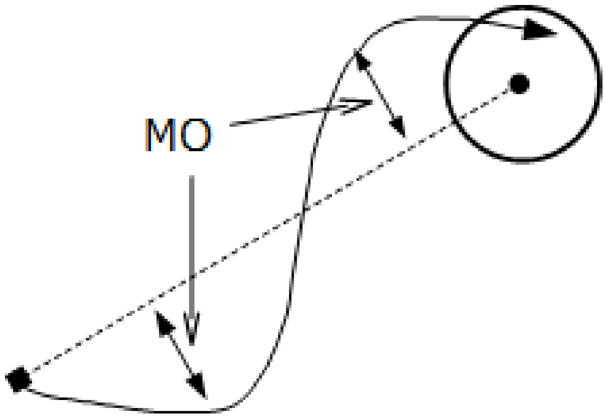


Fig. 7.4 Movement offset

7.2 Experiment Design

A test was designed for the evaluation of the MouthPad's performance, based on the recommendations of the ISO9241-9 standard. The test employed was of the multi-directional point select type (Figure 7.5), and had an effective difficulty index of 3.9 bits. The test involved 15 targets with the diameter of 13 mm, disposed in a circle with the diameter of 180 mm.

The user interface was deployed on a notebook computer, with 4 GB of RAM memory, and a 2.1 GHz dual core processor. The procedure was displayed on an external 19 inch TFT display.

A calibration procedure was performed before each experiment, to optimize the parameters of the system, as described in the previous chapter. The procedure consisted in the adjustment of two parameters, the amplitude of the output signal and the threshold of the analog-to-digital converter. First, the subject adjusted the signal voltage, from a potentiometer on the controller board, to the point where the presence of the signal was felt, but no discomfort was caused. Then the resolution of the interface was adjusted to an optimal level, via the contact threshold.

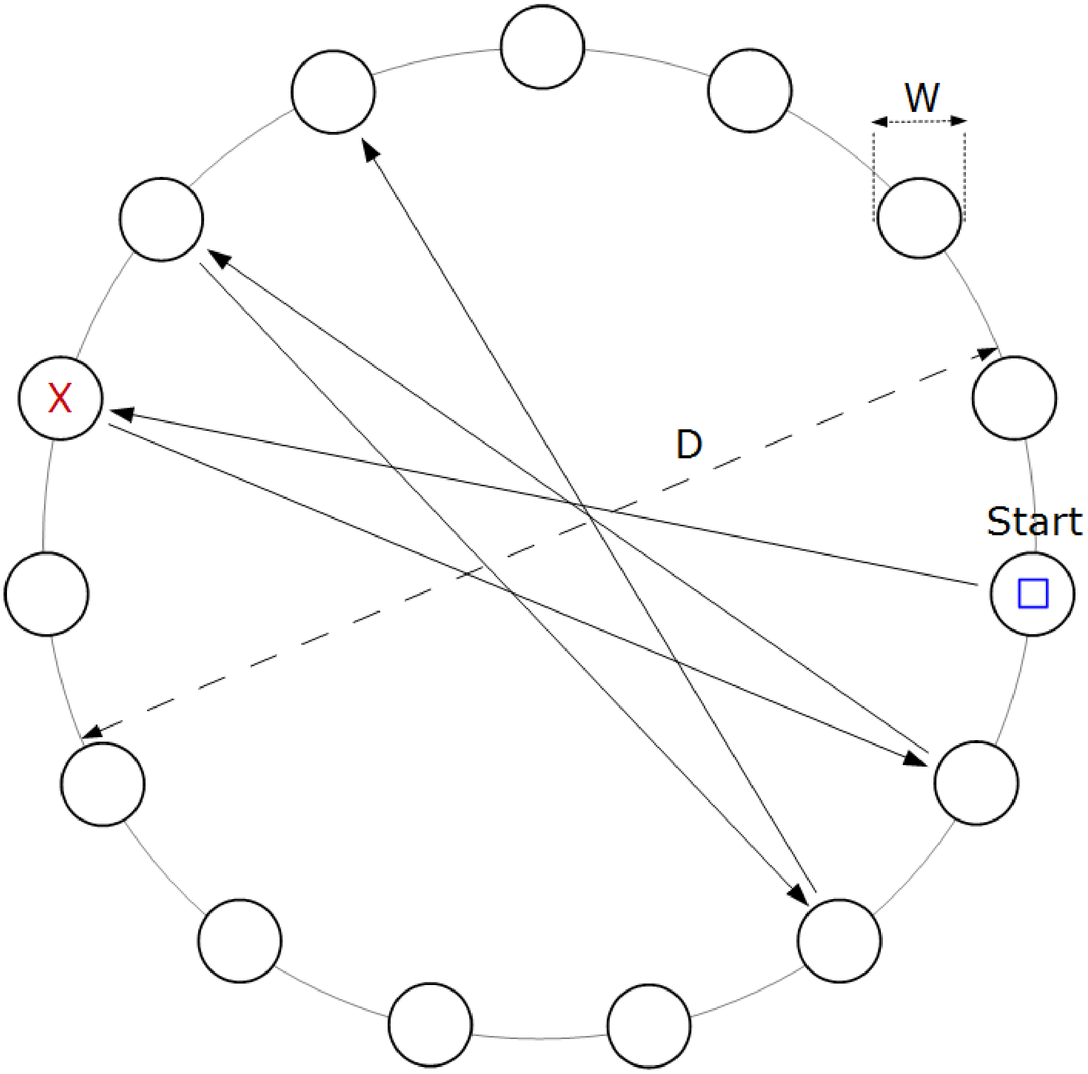


Fig. 7.5 Multi-directional point select task

7.3 Participants

Six able-bodied paid participants were involved; their age ranged from 24 to 44 years, with an average age of 29 years. The subjects were briefed prior to the experiment, regarding the nature of the experiment, and the risks involved. The procedure was explained to them in detail, and they were asked to select all the targets, in the right order, as fast as possible, and ideally without missing any of them.

7.4 Procedure

Each experiment included 25 trials, 15 task selections each, totalling 375 selection tasks per subject and 2250 over the whole experiment. The participants trained for 20 minutes before the actual experiment started. A five minutes break was allowed at the end of every block of five trials.

The experiment commenced when the subject hit the enter key on the keyboard, after being prompted by the user interface to do so. The first of the targets was signalled as available with a red “X”. Upon clicking, whether over the target or not, the next target on the opposite side of the circle was marked with the same red “X”, and so on, until all the targets have been cycled through.

Target selections performed at a distance larger than three times the radius of the target width were considered outliers, and removed from the data collection. Removing outliers from the data was done to avoid erroneous clicks caused by the user inadvertently touching the keyboard.

7.5 Results and Analysis

The mean value of the movement time was recorded for each block of five trials of 75 selections and can be seen in Figure7.6. The mean movement time for the whole experiment was 3150 milliseconds, which is about 50% higher than that of the Interlink DeskStick, the joystick tested by MacKenzie [64].

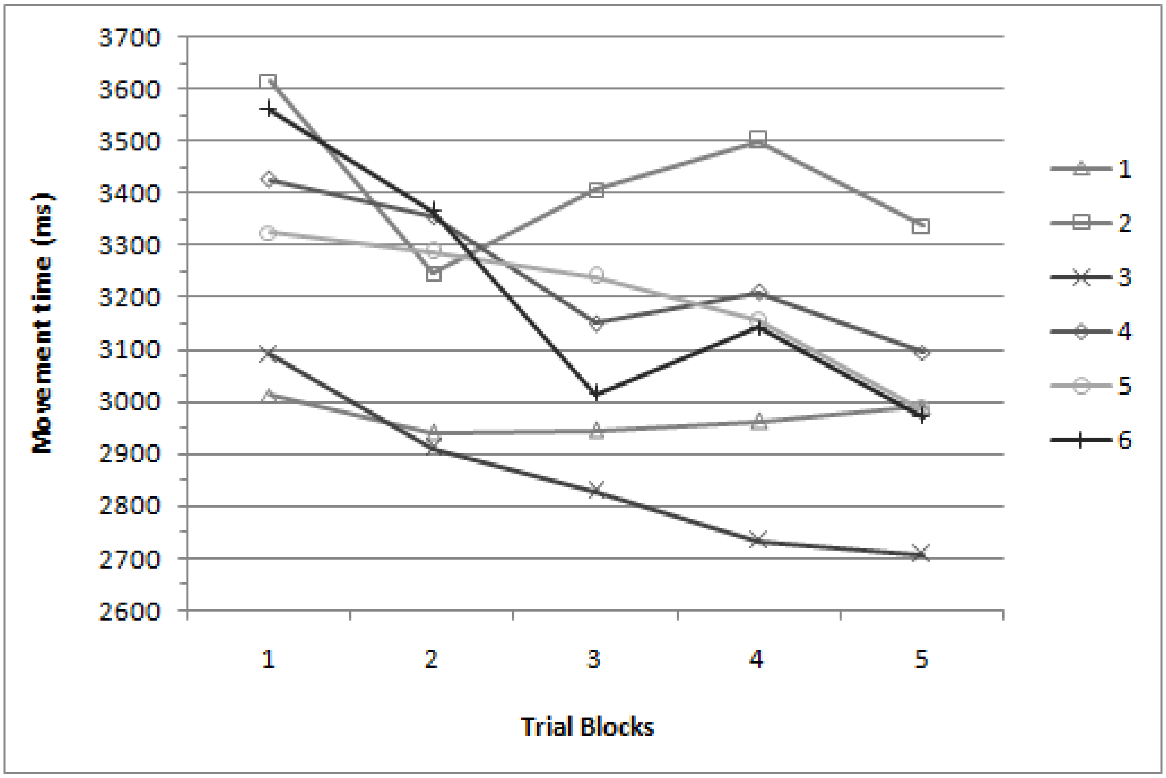


Fig. 7.6 Movement time per subject, over five trial blocks

The mean value of the throughput rate was recorded per trial block, and can be seen in Figure7.7. The overall TP mean value was calculated at 1.67 bps.

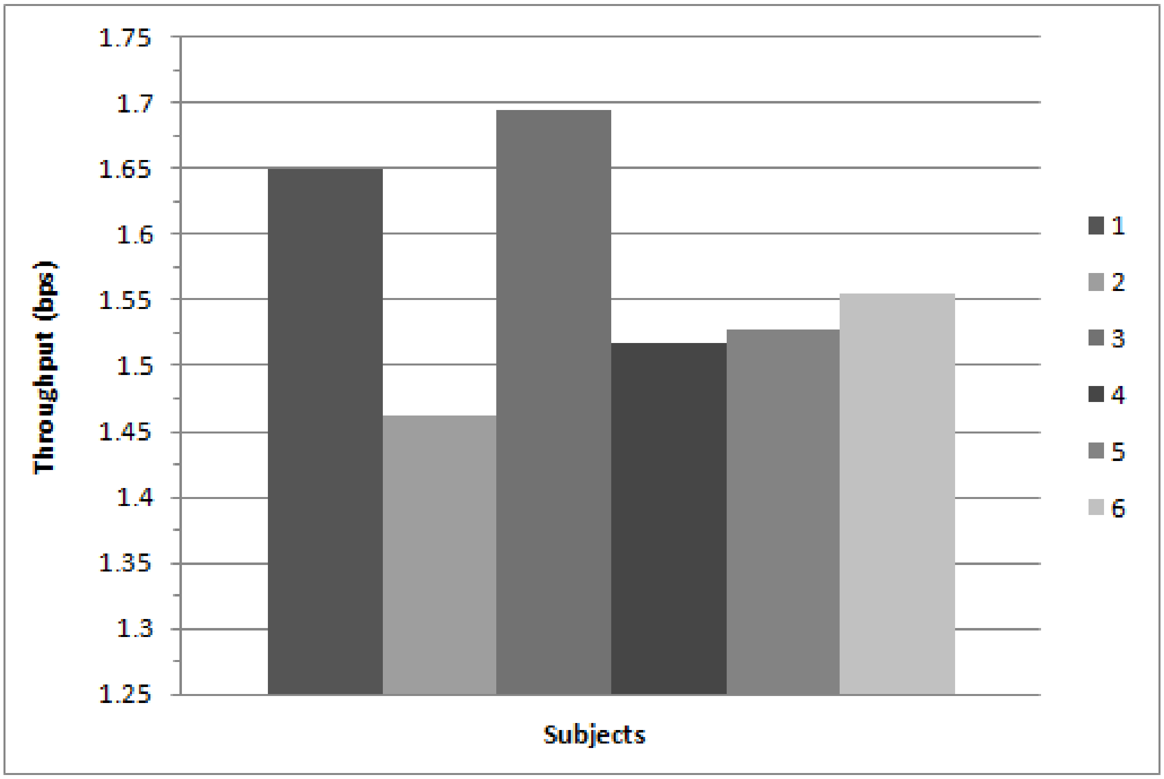


Fig. 7.7 Throughput rates per subject (in bits per second).

When compared with the devices evaluated by Douglas et al. [65], the MouthPad's mean throughput is 78% of that of the isometric joystick TrackPoint III, and 88% of the Interlink DeskStick, as tested by MacKenzie et al. [64].

The error rates were measured as a percentage of missed clicks per each 15 selection trial, and are shown in Figure7.8.

The 2.3 % mean error rate, was quite close to the 2.1 % of the TrackPoint III [64], and significantly lower than that of all the pointing devices tested by MacKenzie [64], which varied between 7 % and 9.4 %.

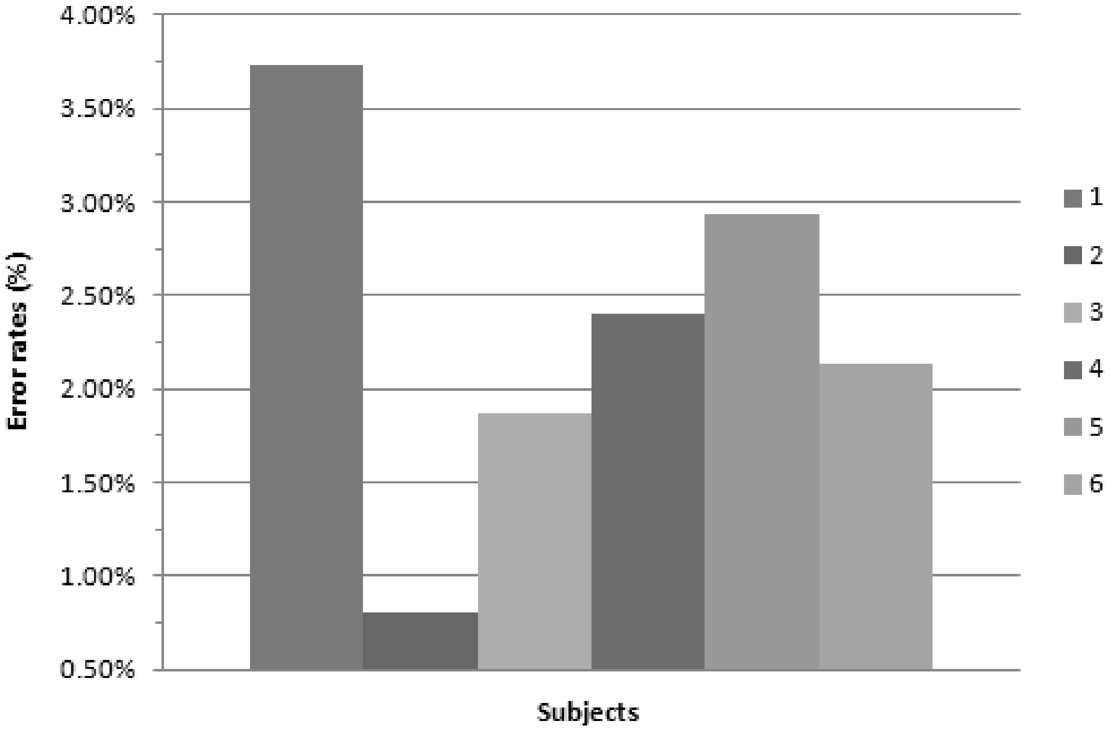


Fig. 7.8 Error rates per subject

Movement offset was recorded in pixels, and is depicted in Figure7.9. With a mean measured at 26 pixels, the MouthPad's MO is about five times higher than the Interlink DeskStick, which was recorded at 5.1 pixels.

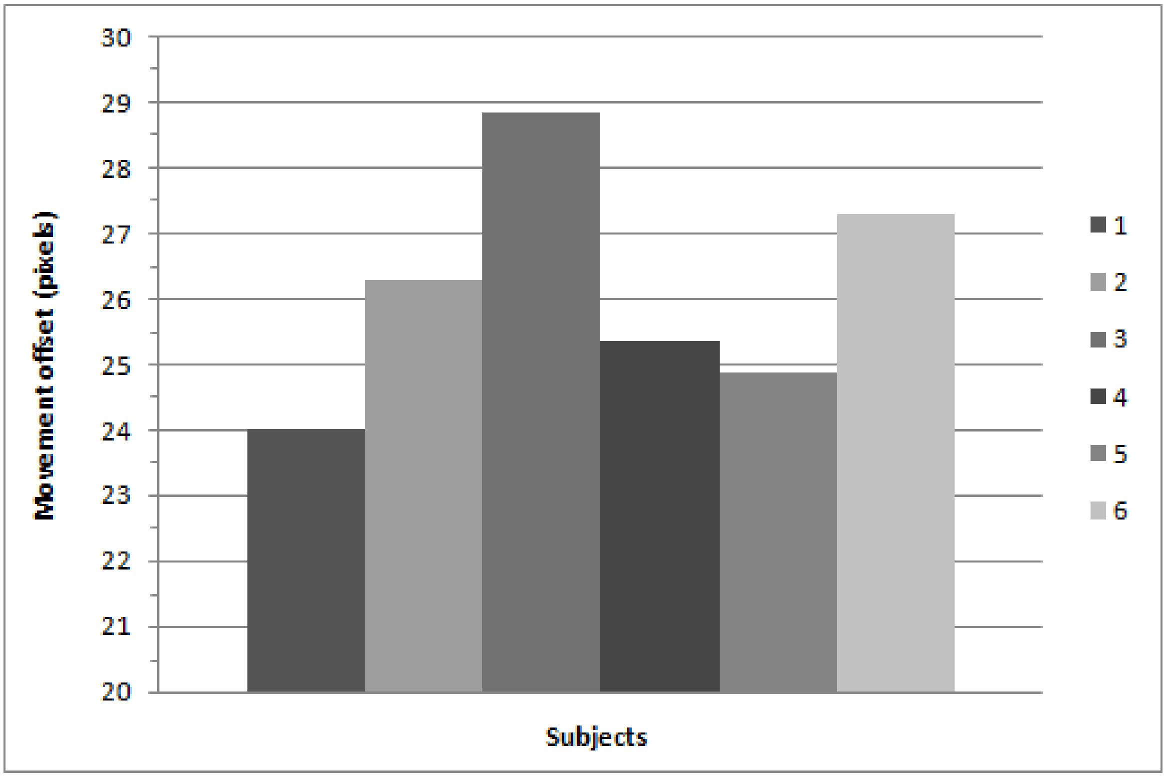


Fig. 7.9 Movement offset per subject

Considering the low resolution of the tongue contact detection mechanism implemented in the MouthPad, a lower accuracy in the pointer's movement was expected.

The target re-entry rate is shown in Figure 7.10. The mean TR value of 0.156 counts per target was comparable with values obtained by MacKenzie [64] for the mouse (0.07), trackball (0.26), joystick (0.33), and touchpad (0.15).

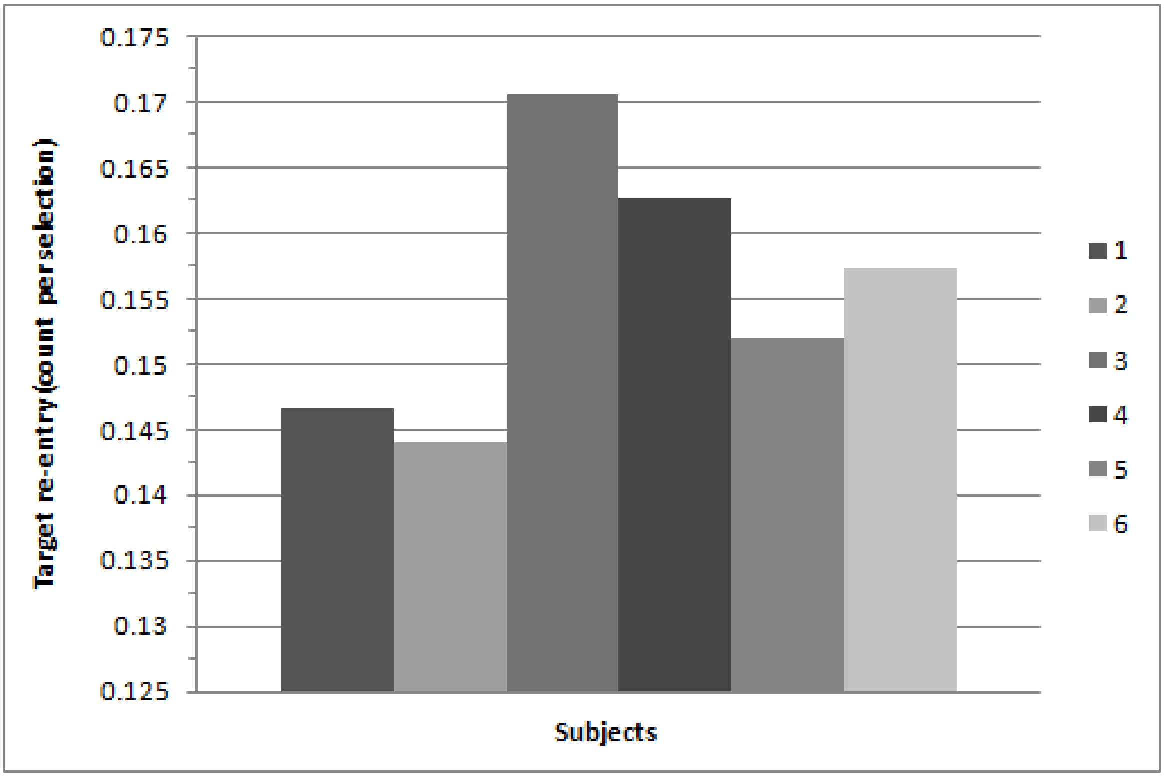


Fig. 7.10 Target re-entries per selection and subject

A decrease over time in the responsiveness of the system was observed. By the end of a five trial block, the resolution of tongue contact mapping was lower than after the calibration. It was noticed that, after a short break, the issue was less noticeable, and it disappeared altogether after wiping clean the tongue device. It was consequently determined that the saliva was the cause. As saliva secretion is triggered by the presence of the tongue device in the mouth, the amount of saliva increases during the usage of the device. The conductivity of the saliva allows the current to reach a larger area on the tongue device, effectively decreasing the resolution of the tongue mapping, hence the lower accuracy of the interface.

The relatively high movement time values suggest a low speed of the interface. The main cause was considered to be the serial communication between the microcontroller and the Bluetooth, on the controller unit. This communication link is limited to 115200 bps, due to hardware limitations in this version of the system. The maximum communication rate in this configuration is between 25-30 frames per second, which translates into 25 to 30 pointer moves per second.

Given that the accuracy of the system is higher than that of a regular joystick, and that the mean throughput is close to that of other pointing devices, it appears that higher accuracy is, unsurprisingly, the consequence of a trade-off with lower speed.

Chapter 8

Conclusions

8.1 Main Contributions

Hands-Free Computer Pointer Control

A new method of controlling hands-free a computer pointer was proposed. This method is based on the mapping of the tongue's position against an intraoral electrode array.

The tip of the tongue is used to close the current outputted by the source electrodes through the sink electrode. The contact impedance between the source electrodes and the sink electrode is monitored in real time. Algorithms have been implemented to allow the system to ignore involuntary tongue gestures.

Each source electrode can be used as a contact when paired with the sink electrode. These contacts are used as joystick switches to determine the direction of the pointer on the screen.

Published Papers

- O. Draghici, I. Batkin, M. Bolic, and I. Chapman, “Performance Evaluation of the MouthPad,” *IEEE International Symposium on Medical Measurements and Applications Proceedings (MeMeA),* pp. 1-5, June 2014.
- O. Draghici, I. Batkin, M. Bolic, and I. Chapman, “The MouthPad: A tongue-computer interface,” *IEEE International Symposium on Medical Measurements and Applications Proceedings (MeMeA),* pp. 315-319, May 2013.

8.2 Other Contributions

Multifunctional Research Platform

A new system was designed and built for the purpose of researching electrical neurostimulation, biofeedback collection, human-computer interfacing, as well as sensory substitution and augmentation.

Both alternating and direct current outputs are available for electrical stimulation. The amplitude, the frequency and the duty cycle of the output signal are adjustable via the firmware implemented on the microcontroller. The amplitude is also adjustable directly on the board, through a potentiometer. Random noise can also be generated, but it was not implemented in the present version of firmware.

The device has built-in safety features that allow for human clinical trials. The level of the current is limited to known safe levels for both the intraoral and the transcranial output channels, while the charge is balanced such that electrode polarization is minimized.

Neurostimulation Method

By providing both intraoral and transcranial electrical stimulation capabilities, the new platform allows for a new neurostimulation method that combines non-invasive cranial nerve neuromodulation (CN-NINM) and transcranial electrical stimulation (tDCS, tACS, and tRNS).

A patent application has been filed in the United States and internationally for a new neurostimulation system, device, and method (13/713,769). In both intraoral and transcranial electrical stimulations, the source and the sink electrodes are placed on the tongue and the on the scalp, respectively. In this new method one of the electrodes is placed intraorally, while the other is placed on the scalp of the subject; this could potentially improve the penetration into the brain, and increase the resolution of the stimulation.

8.3 Future Development

In order to make this system fully usable as an assistive device for computer control, the size of the tongue device should be reduced, such that it would fit on a dental retainer. The intraoral electrode array should be redesigned, to include only the electrode switches, and dedicated electrode switches for click management.

A new version of the controller unit would be needed, dedicated solely to tongue contact monitoring. Such a unit would be embedded in the tongue device, so that the whole system would be wireless, with no external wiring needed.

Another improvement would be the addition of self calibration capabilities by automatically adjusting the A/D threshold. This could be done by periodically monitoring the resolution of the contact map.

8.4 Final Words

The MouthPad is slightly slower than a regular joystick, but more accurate in the selection of targets. This may simply be the result of the user’s approach. It is only natural that first time users would be more careful in the process of target selection, given that this is a new approach to controlling a computer that they have never tried, and it uses a different sensorial path than regular pointing devices.

Despite certain hardware limitations of this version, the MouthPad achieves a level of performance and accuracy comparable to other joystick devices, and has the potential to be used as a pointing device, to control a computer without the use of hands.

This first prototype includes hardware for multiple functions. If used solely for computer control, only a small subset of the respective hardware would be needed.

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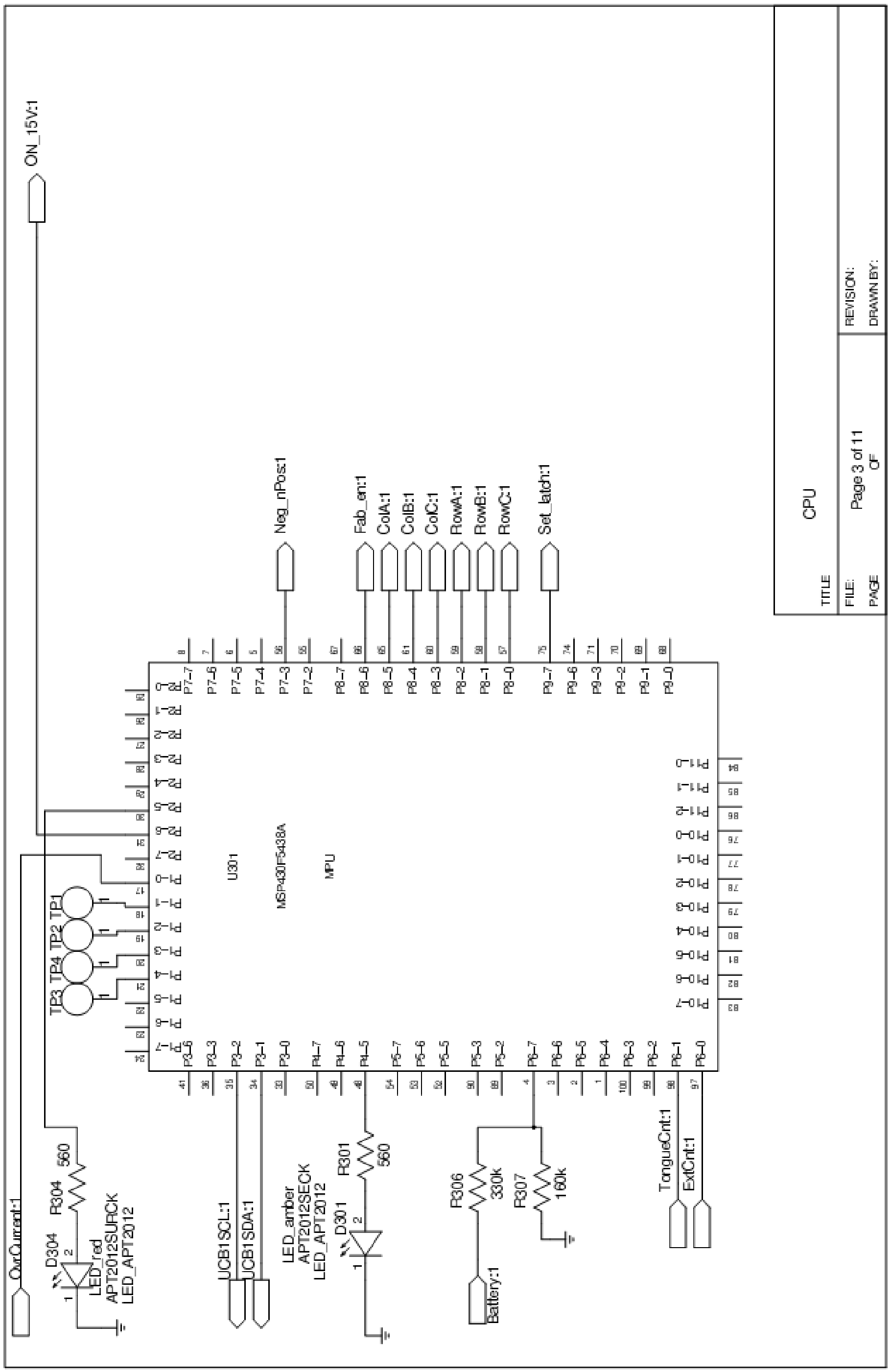
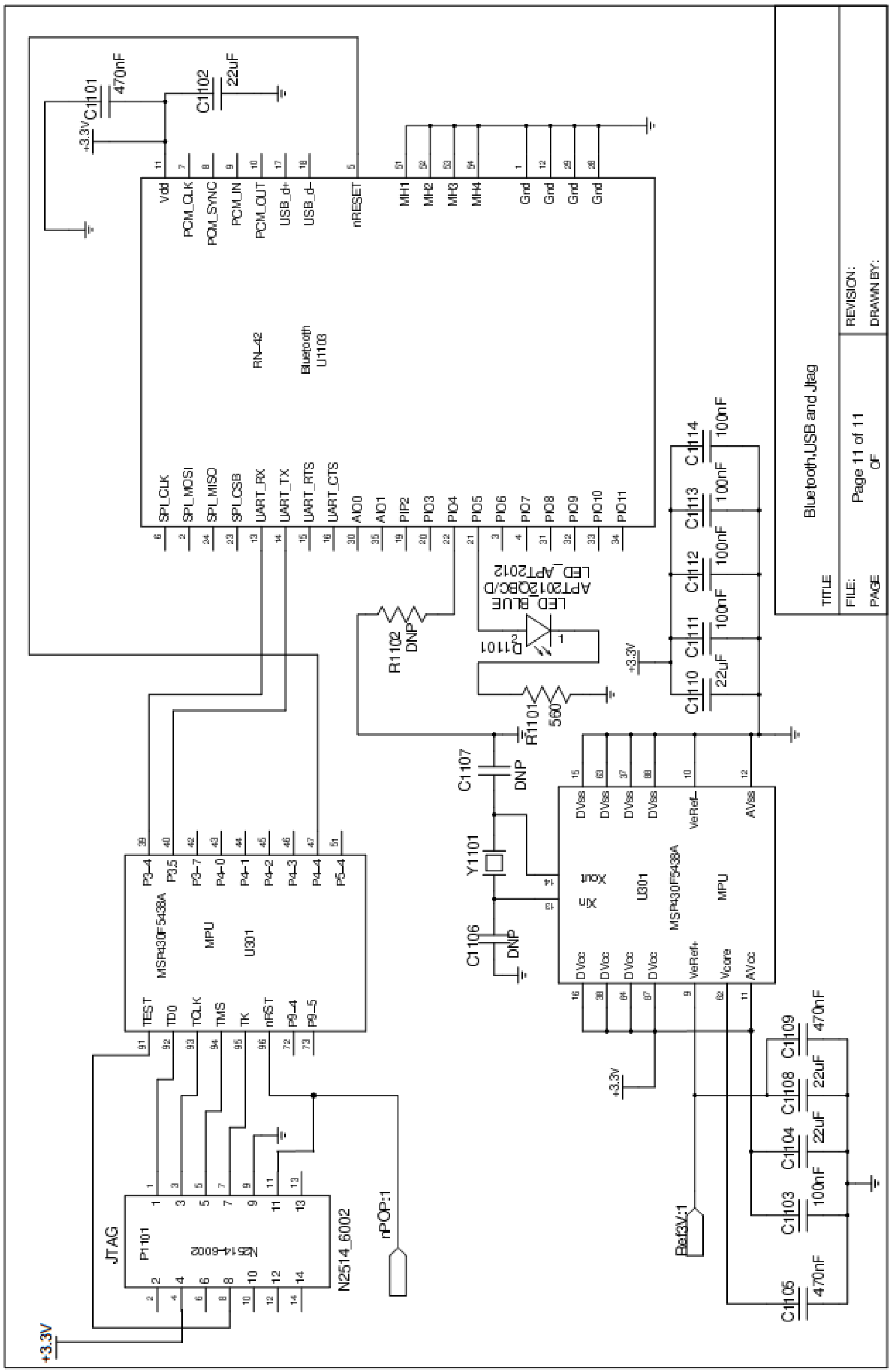
Appendix A - Microcontroller

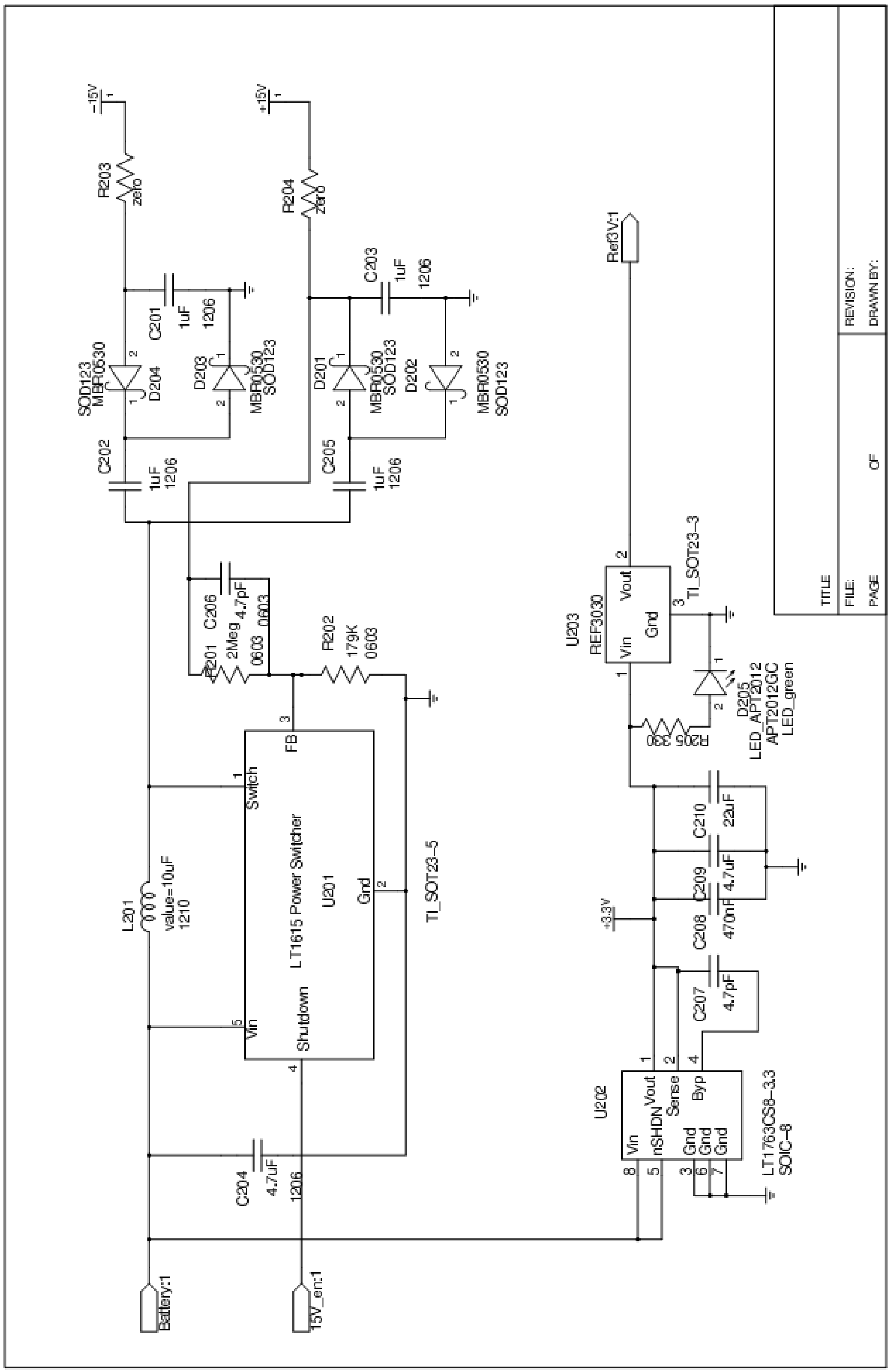


Appendix B - Bluetooth & JTAG



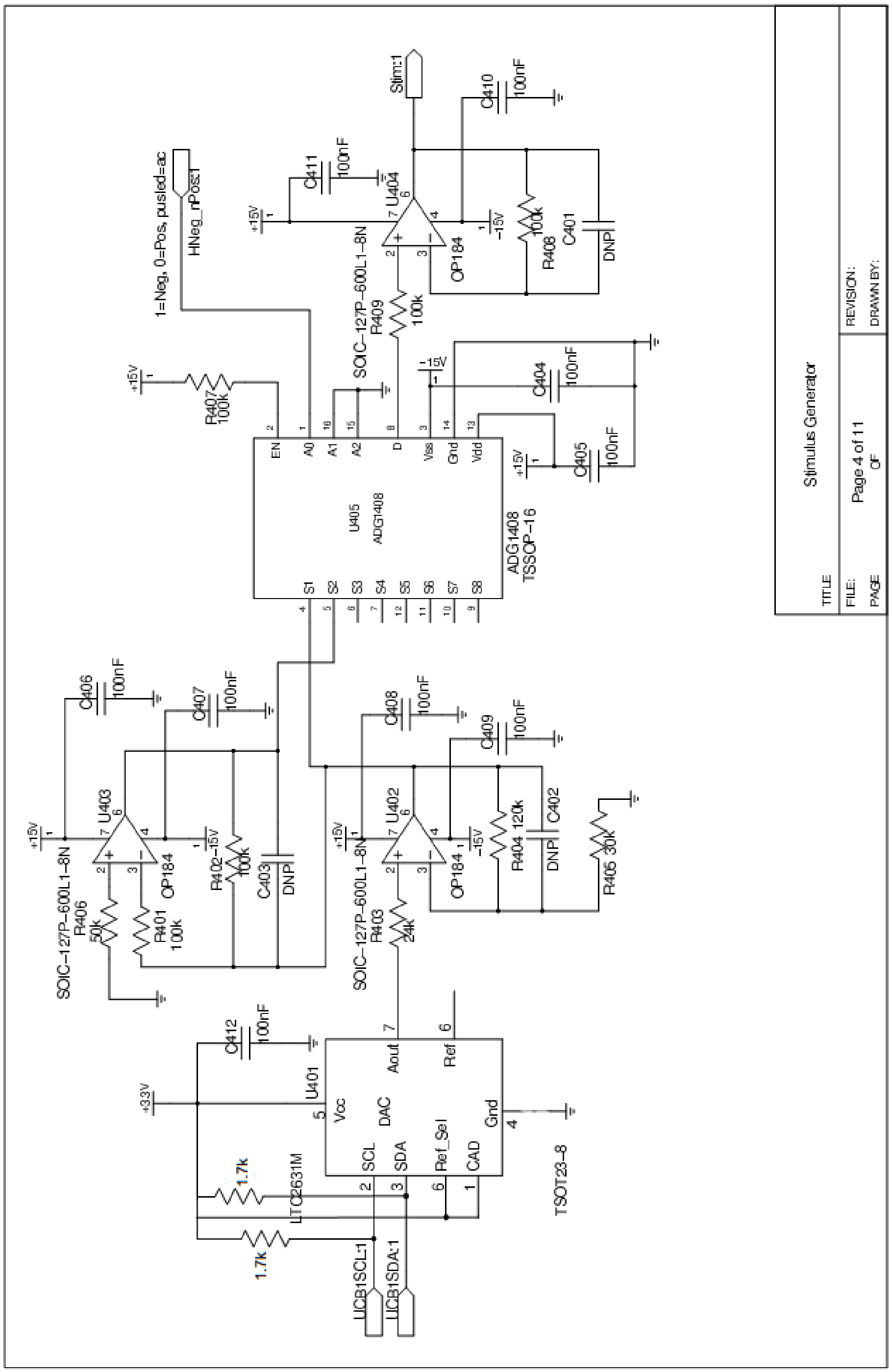
Appendix C - Power Module

Regulator, converter, and reference



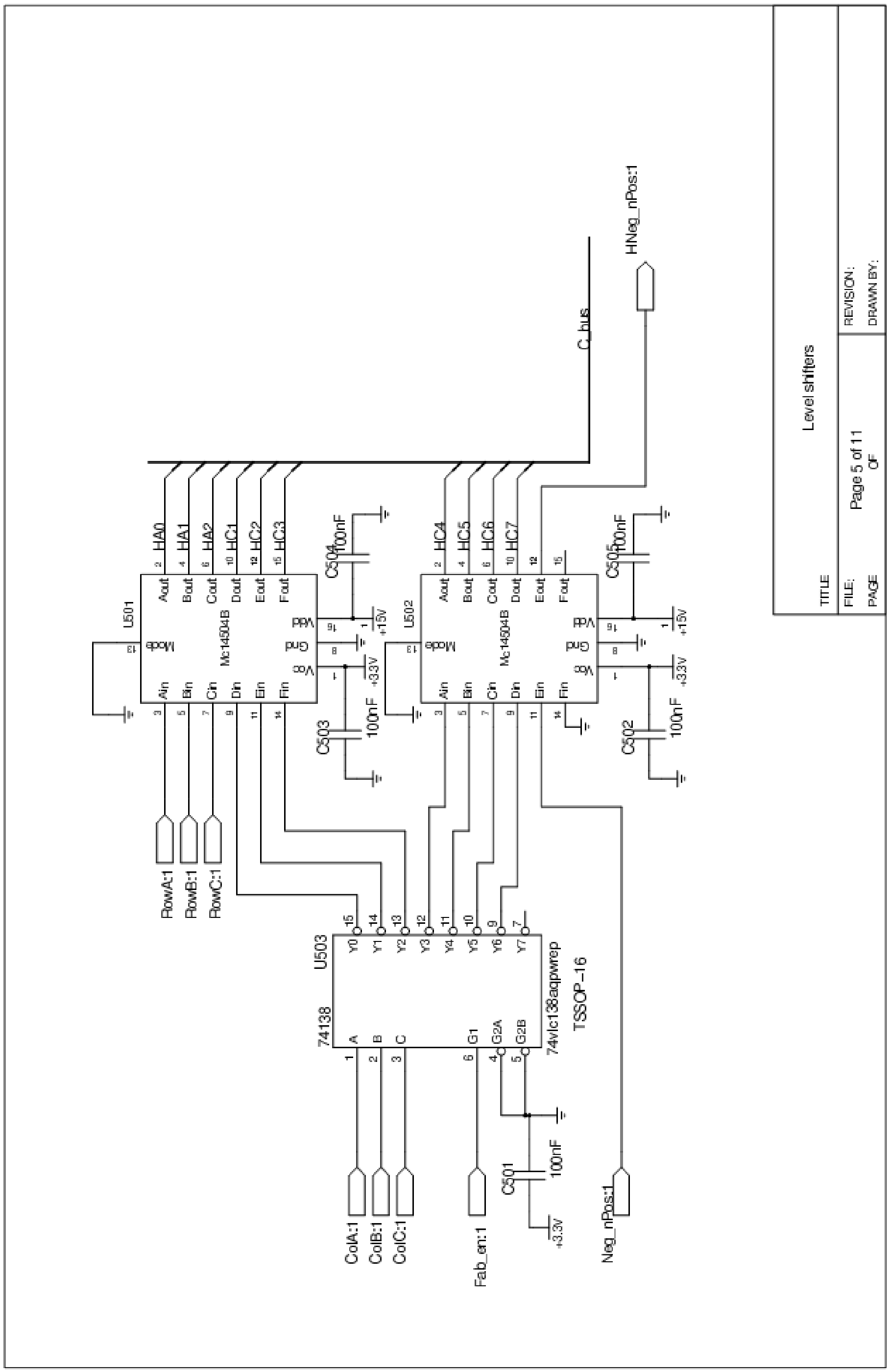
Appendix D - Signal Generator

DAC, amplifiers, and signal chopper



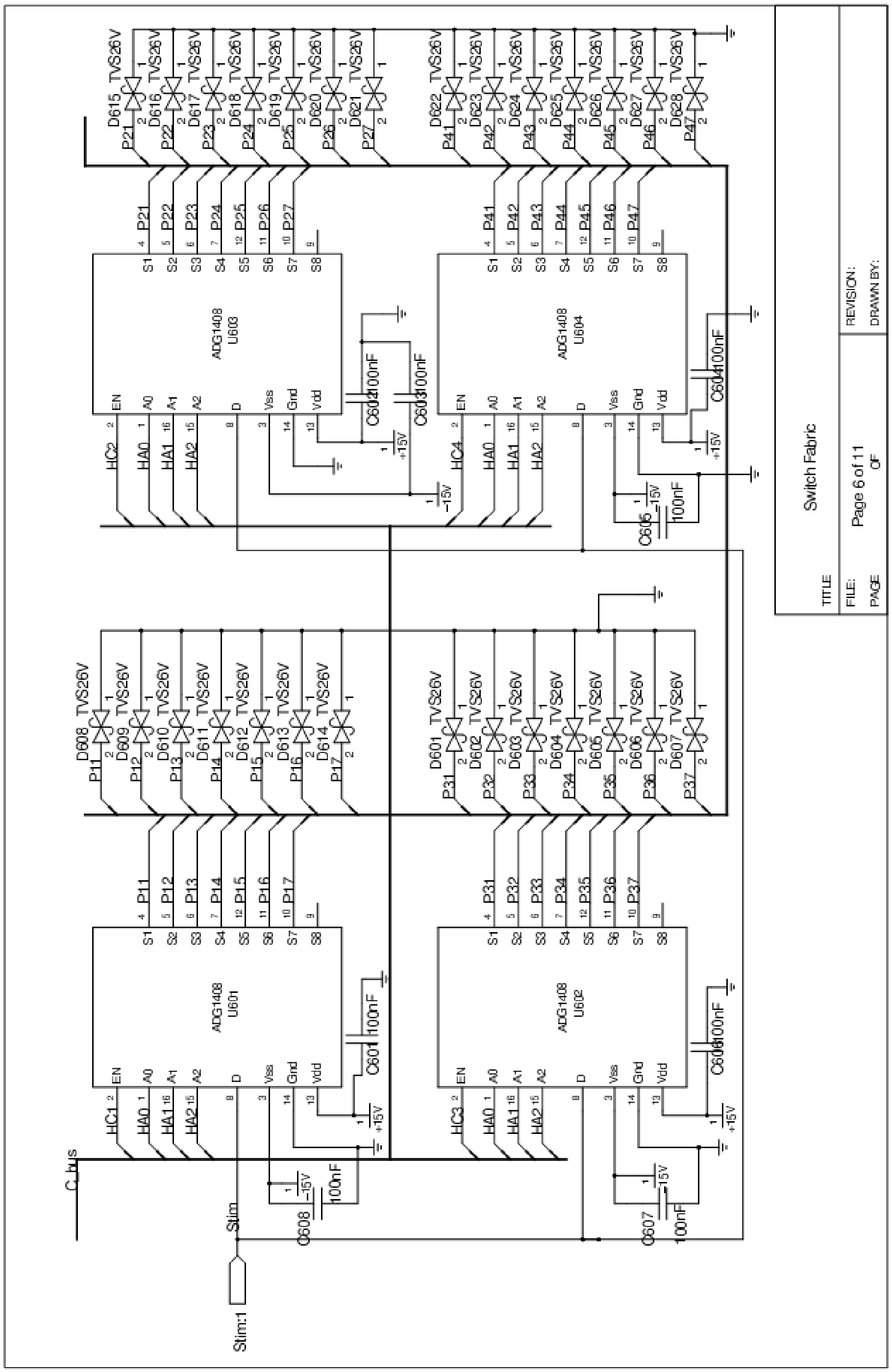
Appendix E - Switching Fabric

Column address decoder and level shifters



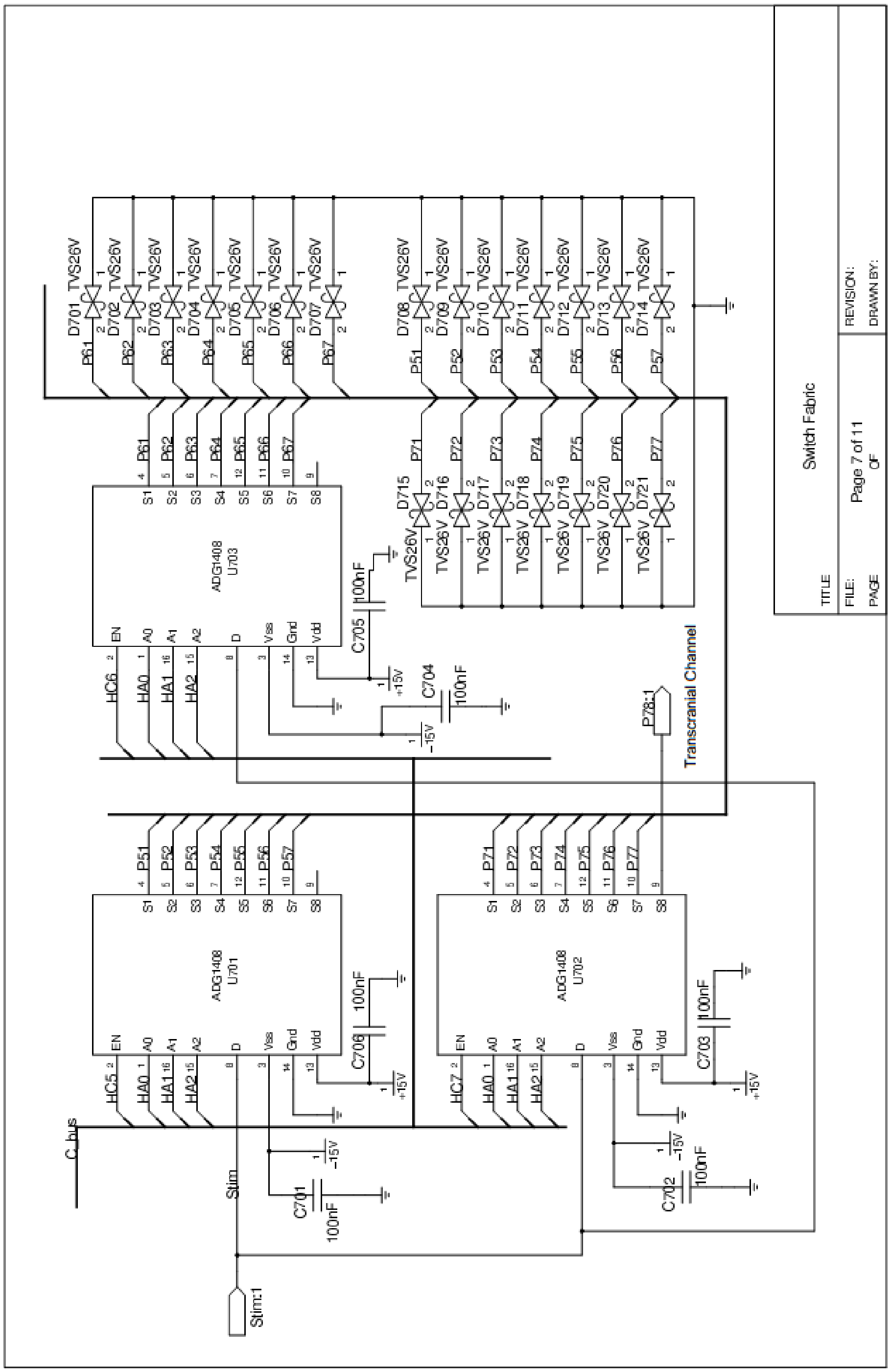
Appendix F - Switching Fabric

Row multiplexers 1-4



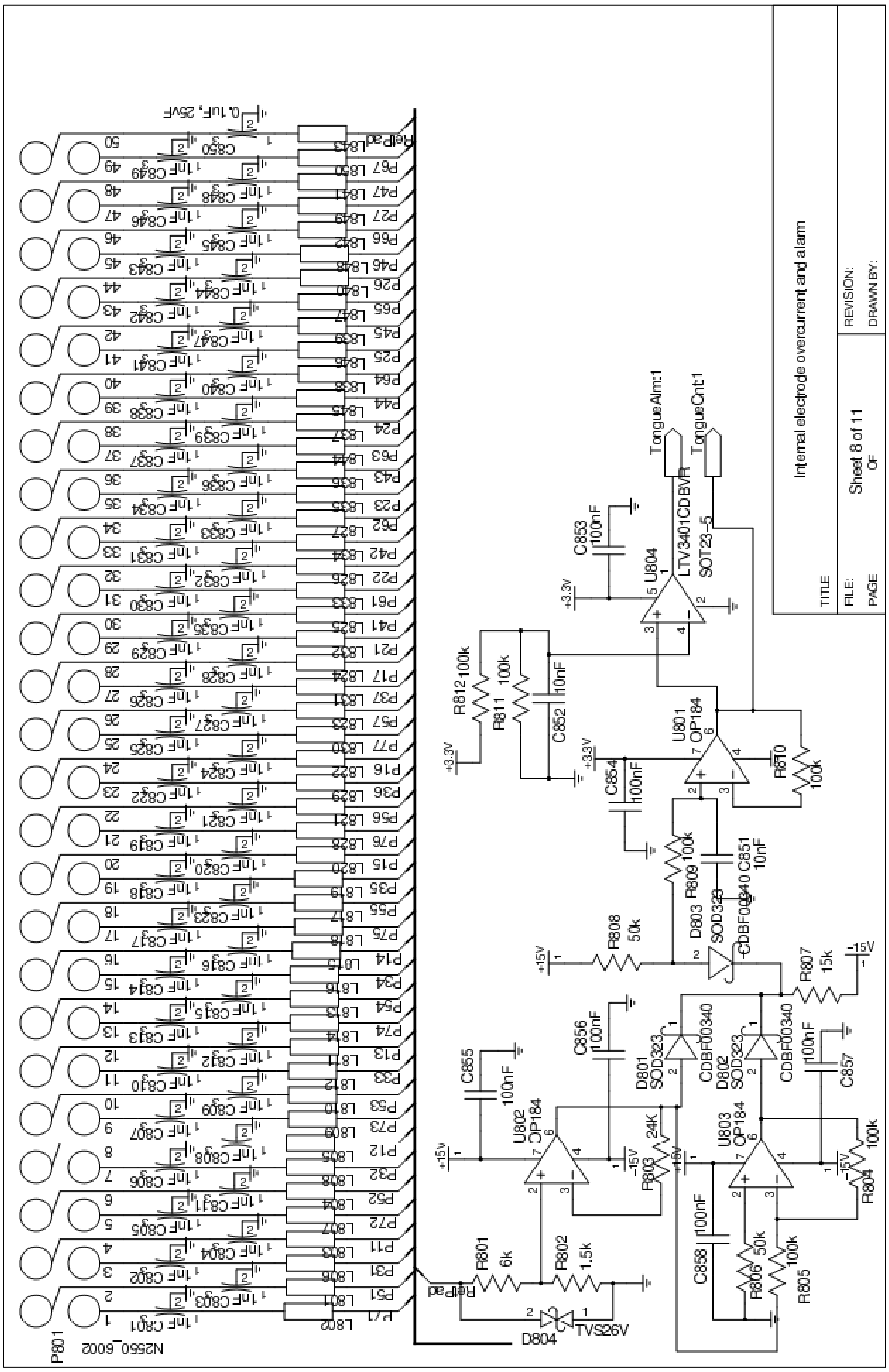
Appendix G - Switching Fabric

Row multiplexers 5-7



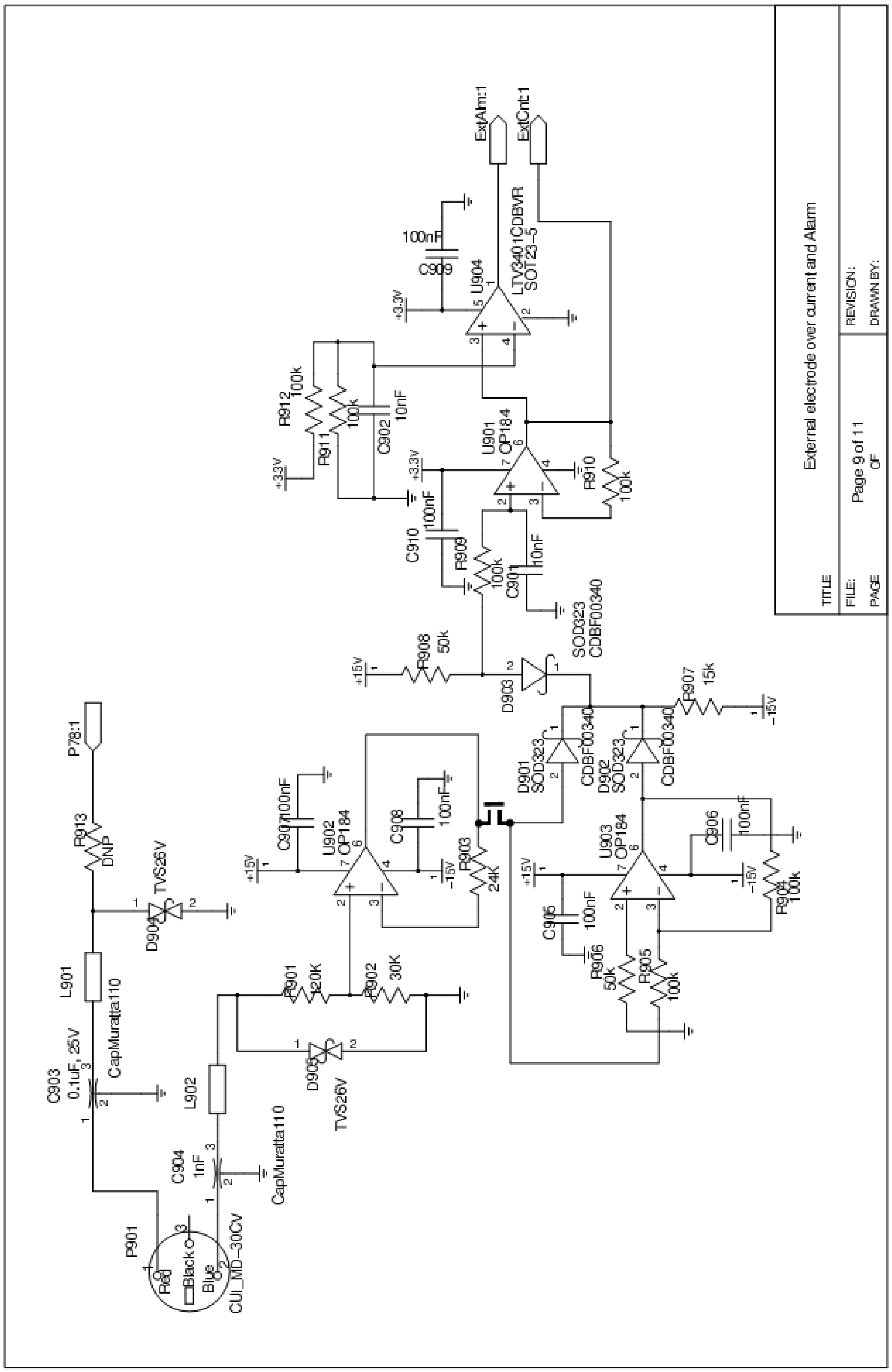
Appendix H–Intraoral Channel

Signal conditioning and safety comparators



Appendix I–Transcranial Channel

Signal conditioning and safety comparators



Appendix J – Safety Switch