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Assistive Technologies for Spinal Cord Injured Individuals

A Survey

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Assistive Technologies for Severe Spinal Cord Injured Individuals: A Survey

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Abstract

Spinal cord injured (SCI) individuals are often deprived from computer access and subsequent control and communication abilities. Their motor skills loss often translates in the inability to operate traditional inputs like the keyboard and mouse pointer devices. Moreover, with the enormous technology evolution in the last few years, our lifes, control and communication depend increasingly on gadgets (i.e., mobile devices). More than just leisure, jobs depend on those technologies. This technological evolution, contrary to what could be expected, has enlarged the damp between disabled and fully-capable individuals and indirectly reduced their life quality. In the past decades several approaches have been made to overcome this problem and re-approach SCI patients to computers or any other electronic device. In this report we review the major approaches to assistive technologies considering spinal cord injured individuals, discussing and comparing both their advantages and limitations.

Contents

1 Introduction

Technology is creating new opportunities for more than 60% of Europe's population, connecting us to better paid jobs, instant information, new forms of social interaction, community infrastructures, government services, consumer power and convenience. It plays an ever increasing role in our day to day lives - in how we communicate, how we carry out business, how we acquire information and how we enjoy ourselves. It touches our lives in ways which we are often unaware of or do not event think about. - **In *e-Inclusion Ministerial Debate 2007 Conference Guide***

We are used to communicate with computers through keyboards and mouse pointer devices. Although several non-conventional input modalities appeared in the last few years the traditional approaches are still overwhelming. For any physically full-capable individual there are several input modalities to choose from and it is a personal choice to use keyboards and mouse pointer devices to operate with computers. A part of the population, due to physical impairments, isn't able to choose and is often incapable of operating with electronic devices. Severe spinal cord injured individuals are a part of this group presenting disabilities that deprive them to operate traditional modalities.

1.1 Spinal Cord Injury

The spinal cord is the largest nerve in the body extending from the brain to the waist. The nerve fibers inside the spinal cord carry *messages* between the brain and other body parts to enable sensory, motor and autonomic functions. The nerves within the spinal cord, named upper motor neurons, carry messages back and forth between the brain and the spinal nerves. The nerves that branch out from the spinal cord, named lower motor neurons, carry sensory information and motor commands between the spinal cord and other areas of the body. These nerves exit and enter at each vertebral level and communicate with specific areas of the body (Figure 1).

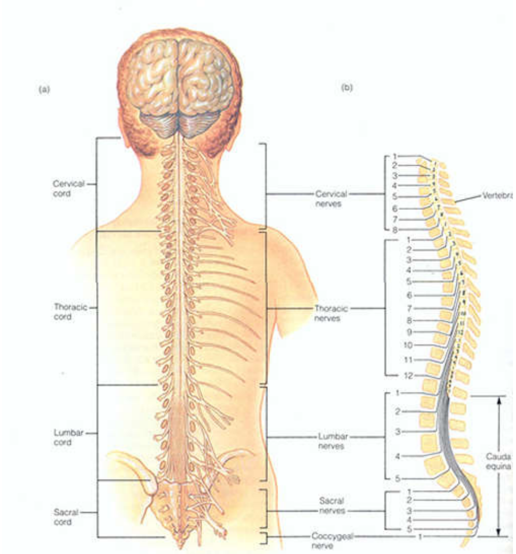


Figure 1: Spinal Cord

Spinal cord injury (SCI), or myelopathy, is a disturbance of the spinal cord that results in loss of sensation and mobility. Spinal cord injuries can affect the communication between the brain and the body systems that control sensory, motor and autonomic function below the level of injury. It is important to note that the spinal cord does not have to be completely severed for there to be a loss of function. In fact, the spinal cord remains intact in most cases of spinal cord injury. In general, the higher in the spinal column the injury occurs, the more dysfunction a person will experience.

The eight vertebrae in the neck are named cervical vertebrae. The top one is called C1 and the next C2. Injury of cervical nerves between C1 and T1 (first thoracic vertebrae) could result in tetraplegia (formerly called quadriplegia). Depending on its vertebral level and severity, the individuals with tetraplegia experience a loss of motor and/or sensory functions in their head, neck, shoulders, upper chest, arms, hands and fingers. Injury between C1 and C4 is usually called high tetraplegia, while injury between C5 and C8 is called low tetraplegia. A person with low tetraplegia may still have partial motor/sensory function in his shoulder, arms, and wrists. Injury between T2 and S5 could cause Paraplegia (Figure 2). Depending on the severity of the SCI, individuals with SCI may experience complete or incomplete loss of motor/sensory function below the level of injury. The exact effects of a spinal cord injury vary according to the type and level injury, and can be organized into two types:

- In a complete injury, there is no function below the level of the injury. Voluntary movement is impossible and physical sensation is impossible. Complete injuries are always bilateral, that is, both sides of the body are affected equally. A person with an incomplete injury retains some sensation below the level of the injury.
- Incomplete injuries are variable, and a person with such an injury may be able to move one limb more than another, may be able to feel parts of the body that cannot be moved, or may have more functioning on one side of the body than the other.

1.2 Motivation

The limitations imposed by spinal cord injuries deprive the injured individuals from operating electronic devices like computers or mobile devices. Besides the drastic quality of life reduction directly imposed by the impairments, individuals also face a communication shutdown as they are often incapable of operating devices that make possible to communicate with others (computer, cell phone, PDA).

Moreover, as new technologies appear and communication channels increase, the damp between full-capable individuals communication capabilities and the severely disabled ones also increases. The technological evolution influences negatively the disabled population as their inhability to operate and communicate with the new technologies damages the social interaction but also their integration within the society as active members and, particularly as workers who also need to guarantee survival.

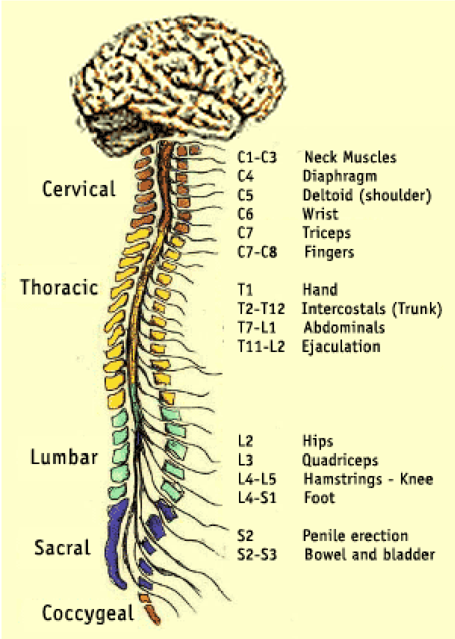


Figure 2: Motor Map

It is a world wide concern to restitute disabled users communicative and control skills to improve their life quality. Hence, by regaining computer control disabled can through it operate any other device, easing their communication, movement and overall autonomy.

Moreover, studies show that nearly 60% of the lesions occur between 16 and 30 years old and that nearly 60% of the impaired were working before the injury while only 20 % are working, one year after the injury. Several factors affect the employment after the lesion and those include the severity of the injury, gender, race, age, marital status and level of education. Although the impairments prohibit to execute some functions, it is possible to aid a great percentage of spinal cord injured individuals to achieve their working goals with auxilliary mechanisms and proper training. The ability to continue working faces benefits that go beyond financial and social advantages: studies suggest that employment is related to prolonged survival (McKinley, 2004).

1.3 Assistive Technologies

Assistive Technology is a generic term that includes assistive, adaptive, and rehabilitative devices that promote greater independence for people with disabilities. Computer control and the subsequent electronic device or even ambient control is a actual world wide concern because it offers people with disabilities the ability to improve their quality of life. Actually through computer control several others devices can be actuated and by that means offering disabled higher freedom and independence levels.

The ability to operate a PC is extremely valuable nowadays, particularly for persons with disabilities. Among other things, the computer can be used to access the Internet, read or compose emails, listen to music, watch movies, or play games. Given the right interfaces, computers can even control a mobile robot or an electric-powered wheelchair , as well as switch lights or other appliances on and off. To say the least, a computer can help very much with the integration of disabled individuals into society.

Unfortunately, the standard way of operating a PC requires the reliable use of hands and arms, since it involves a keyboard and a manual mouse device, which is unsuitable for a large number of people with disabilities. Therefore, developing an alternative user interface, which does not require manual input, is of great importance.

This fact is even more drastic when we consider mobile devices where other variables appear.

For individuals with high tetraplegia, input sources for human-computer interface are limited. Possible input sources include head movements, voice, eye movements, or muscles on the face. For individuals with a lower injury degree some other options can be explored accordingly to the individuals disabilities, like hand joysticks, switches or even monitoring arm muscles.

1.4 Interfacing Schemes

According to (Cook and Hussey, 2002), the human/technology interface is composed by three elements that contribute to the operation of the device: the control interface, the selection set and the selection method. The control interface (i.e., keyboard, switch) is the hardware by which the user operates the device while the selection set is the items available to select from (i.e., icons, letters) and the selection method is the way the user makes selections using the control interface.

Considering selection method or interfacing scheme, we consider two different approaches: direct selection, indirect selection (scanning and coded access).

Direct selection involves a one to one correspondence between input acts and selections (i.e., QWERTY keyboard). In this method, the user identifies a target in the selection set and goes directly to it. As an example of direct selection, we can mention the traditional QUERTY keyboard typing. Obviously, direct selection methods offer a direct correspondence between selections and actions thus it is normally easier to use and quicker. On the other hand, if a selection set is large and the control interface (selected accotdingly to the user's capabilities) has a reduced communication bandwidth, direct selection is not usable.

Scanning entails offering the user, sequentially or otherwise, selection alternatives until the user has indicated his choice. Scanning input is widely exploited in cases of severe disability, since it remains feasible even when a user is only capable of single switch operation (Damper, 1986). In this scenario, even with a large selection set and a reduced communication bandwidth, the user is able to operate the device and accomplish the desired task.

Encoding employs a specific pattern of input acts to make a given selection (i.e., Morse code - Figure 3). In coded access, the user uses a distinct set of actions to input a code for each item in the selection set. Like scanning, coded access requires less physical capabilities than direct selection (Cook and Hussey, 2002). However, in an encoding scenario, the control is on the user side while in a scanning scenario, the device times and controls the interaction.

The choice of an assistive technology must consider this three components and must always be focused on the user and his needs. Almost all devices permit access though

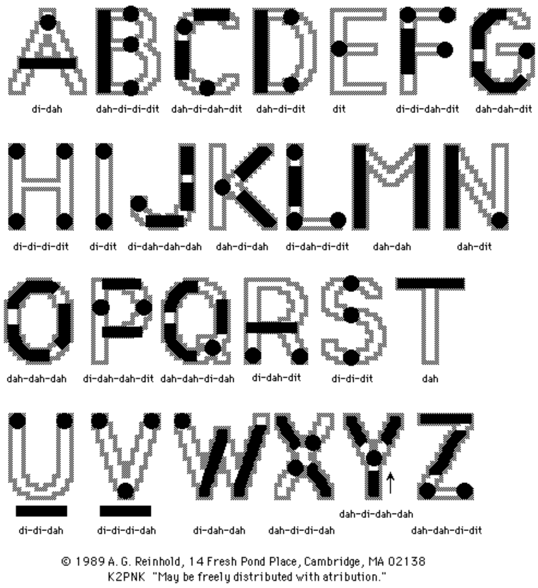


Figure 3: International Morse Code

any type of control interface and selection method. Moreover, the selection set can be adapted to the user.

Although this document follows a control interface-based organization, the research projects and available products' description takes the possible selection set and selection method into account. In fact, the connection between a control interface, selection method and selection set defines the human-technology interface effectiveness.

1.5 Evaluation and Assessment Criteria

To select an appropriate assistive technology several factors must be considered. The level of impairment strongly influences the decision but residual capacities should also be taken seriously into account as a good matching between the user and the selectd modality can highly influence his life quality. For example, it is important to notice that individuals with low tetraplegia, with restricted but residual finger and arm motion, can be provided with some keyboard adaptations to achieve its control with no need for an extra entry interface (i.e., a Keyguard (Figure 4) for individuals with finger function compromised who are willing to make several typing errors). On the other hand, for the most severe injuries an extra computer communication channel must be supplied.

When selecting an input device and interfacing scheme it is very important for clinicians, technologists, caregivers and the disabled themselves to be aware of the assistive technologies characteristics and their suitability to specific cases (Bates, 2002). In this survey, we present the main approaches on assistive technologies

Figure 4: Keyguard

considering SCI, reviewing the state of the art on Switches, Tracking, Electrophysiological, Speech, Hybrid as well as other less explored approaches. We present the methods' advantages and disadvantages comparing them considering:

Potential users range (Card et al., 1990) argued that the manipulation and control requirements of an input device maybe mapped using a design space (Bates, 2002). Considering a certain input modality we can also argue its suitability to a certain person according to the input requirements and the person's sensory and motor characteristics. Thus it is possible to create a map that relates physical abilities with a certain input modality. This is the most important feature of an assistive technology as it presents the total inability of relations between certain impairments and input modalities. All the other features are complementary and can help a certain user to select an assistive technology from the available range, considering his disability and the desired interaction scenarios. We will refeer to the disability level but also include details on required capabilities as the spinal cord lesion level can sometimes be misleading (i.e., incomplete spinal cord injuries).

Dimensionality and Input Speed Several factors influence the interaction speed, whether on the user side (i.e., cognitive load, preparation time) as on the machine (i.e., recognition delays). However, one of the most important issues considering input speed is its dimensionality and therefore its suitability or restrictability to a certain interfacing scheme (direct selection, encoding or scanning). Naturally, the input speed of a certain interface is highly connected to the interfacing scheme used and this one is normally determined by the individual and input source capabilities.

Accuracy, Robustness and Repeatability The accuracy of a certain input mechanism is vital to its adoption. Indeed, if a user is not confident on a certain system he will probably drop its use. This issue assumes great importance when considering assistive technologies where motivation and confidence must be built and mantained.

Ease of use As with accuracy, it is extremely important that a user can easily learn to use an input device. The first approach to a certain technology should be smooth and the user must be able to feel his improvements in the first times he uses the system. Moreover, we must consider that some assistive technologies require the set up of extra components whether in the wheelchair or bed, whether in the user's body. This setup must be simple so caregivers can easily undertake it and dismiss any professional aid. Also, this process must be evaluated considering the time to setup and train (if neccessary) the system.

Aesthetics, Hygene and Acceptance Assistive technologies can be used to aid controlling the computer, an environmental control system or a telephone, among others. Although the majority of these functions are realized in a restricted environment where aesthetics and social acceptance can be minor issues, mobility scenarios must be considered. Several assistive technologies research projects aim at wheelchair control, therefore considering situations in public. Also, in the communication era we are witnessing mobile devices are everywhere and mobile device control for the disabled is also a research issue nowadays. Therefore, it is important to evaluate the technologies aesthetics and social acceptance. Considering user acceptance it is also important to evaluate the awakwardness of some devices. This includes hygiene issues but also some intrusiveness that some technologies imply.

Mobility Adequacy The majority of the assistive technologies are aimed at special purpose devices, mostly personal computers and wheelchairs. Those are normally restricted to a rigid setup and require, for example, that the user faces the computer at a determined distance (i.e., Tracking Interfaces). Also, mobile devices have had an enormous growth in the last few years and almost everyone has one. These small and lightweight devices are carriable and always available. Hence, we will evaluate assistive technologies considering their mobility adequacy, whether in an indoor environment, considering the distance of interaction, whether in an outdoor environment where the surrounding noise, illumination variations, and movement can restrict or deny its use.

Maturity, Availability and Cost The commercial availability of a certain technology argues in its favor. On the other hand, when studying some technologies, although the promising results, we can state that they are still far from a commercial maturity state. The maturity and availability play an important role when considering the users, as the choices must be done in a short-term basis. One of the factors that can influence both the availability but also, besides it, the acquisition of a certain technology is its production cost. Obviously, this cost is reflected in the final product price, that can be sometimes prohibitive for the common user.

Figure 5: Technologies surveyed

1.6 Document Overview

In this document we will survey the main assistive technologies approaches considering computer control by spinal cord injured individuals. Although we are focusing on SCI individuals, these technologies also suit other focus groups depending on their motor and cognitive capabilities.

We undertook an in-depth study on several assistive technologies for severe spinal cord injured individuals. Chapters 2-7 overview those technologies and the most relevant approaches to their use to augment SCI individuals communication and control capabilities (Figure 5). It is important to notice that several soft adaptations can also be used when the impairness is not so severe as the ones described in this document. As an example, an individual with finger extensors and flexors impairness may operate the keyboard with the neccessary aids. A decision map for the adaptations required to overcome these kind of limitations is presented in Figure 6 (Keyboard Assessment Needs) and 7 (Mouse Assessment Needs). The scope of the remainder of this document is focused on the cases where no soft adaptation is possible and the user is unable to operate electronic devices.

It is also relevant to notice that a quadriplegic individual is normally in a wheelchair or laying in a bed/couch. Therefore the first obsctacles they need to overcome are the physical position of the device, its reachability, and other physical control functions like using a diskette drive or a CD-ROM (Kotzé et al., 2004). Some spinal cord injured individuals with low tetraplegia are still able to move around and use their residual arm/hand/finger motions to accomplish these tasks but the most severe cases are unable to do so as below neck function is inhexistent. Although this is a

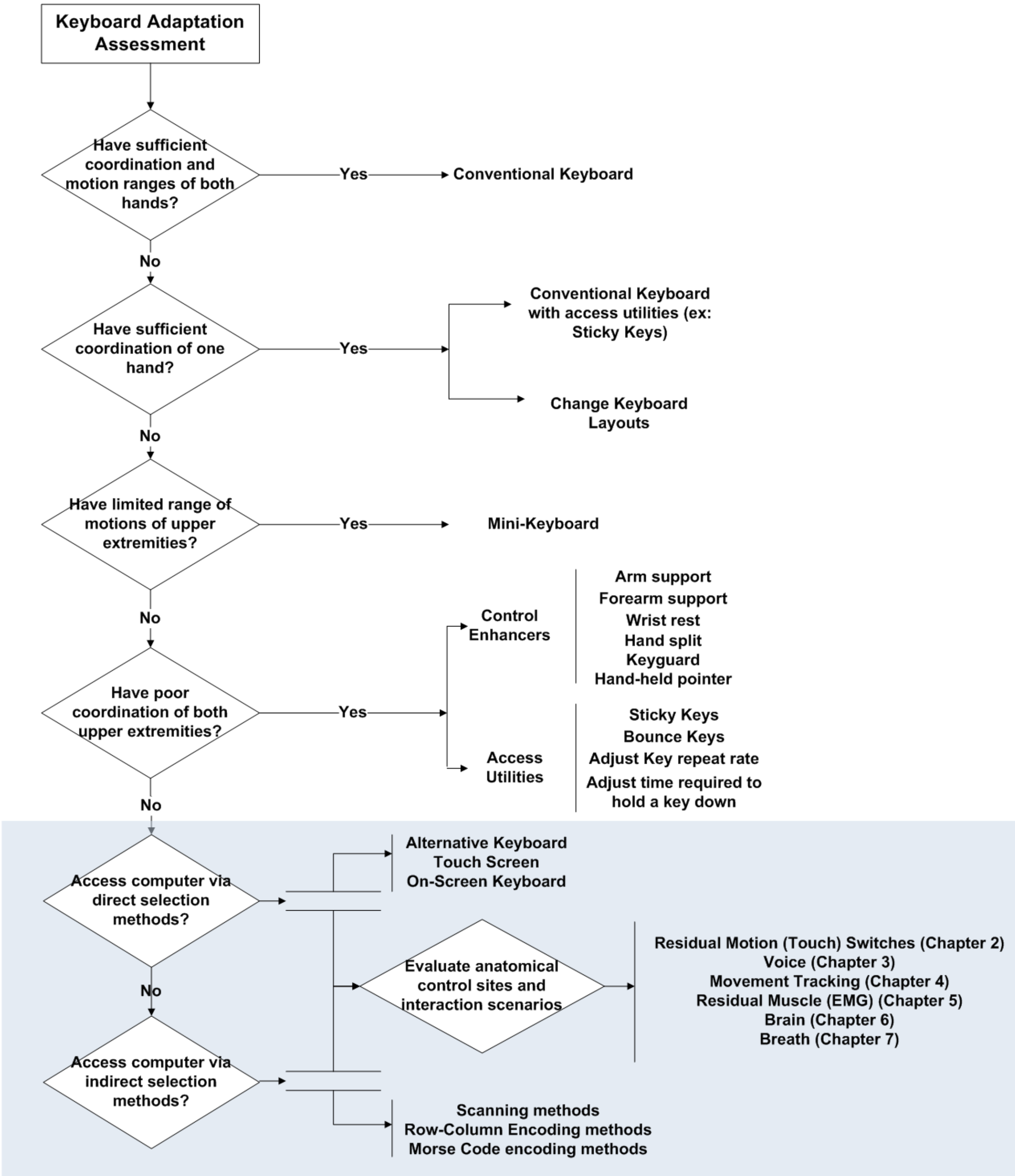


Figure 6: Keyboard Assessment Needs (adapted from (Wu et al., 2002))

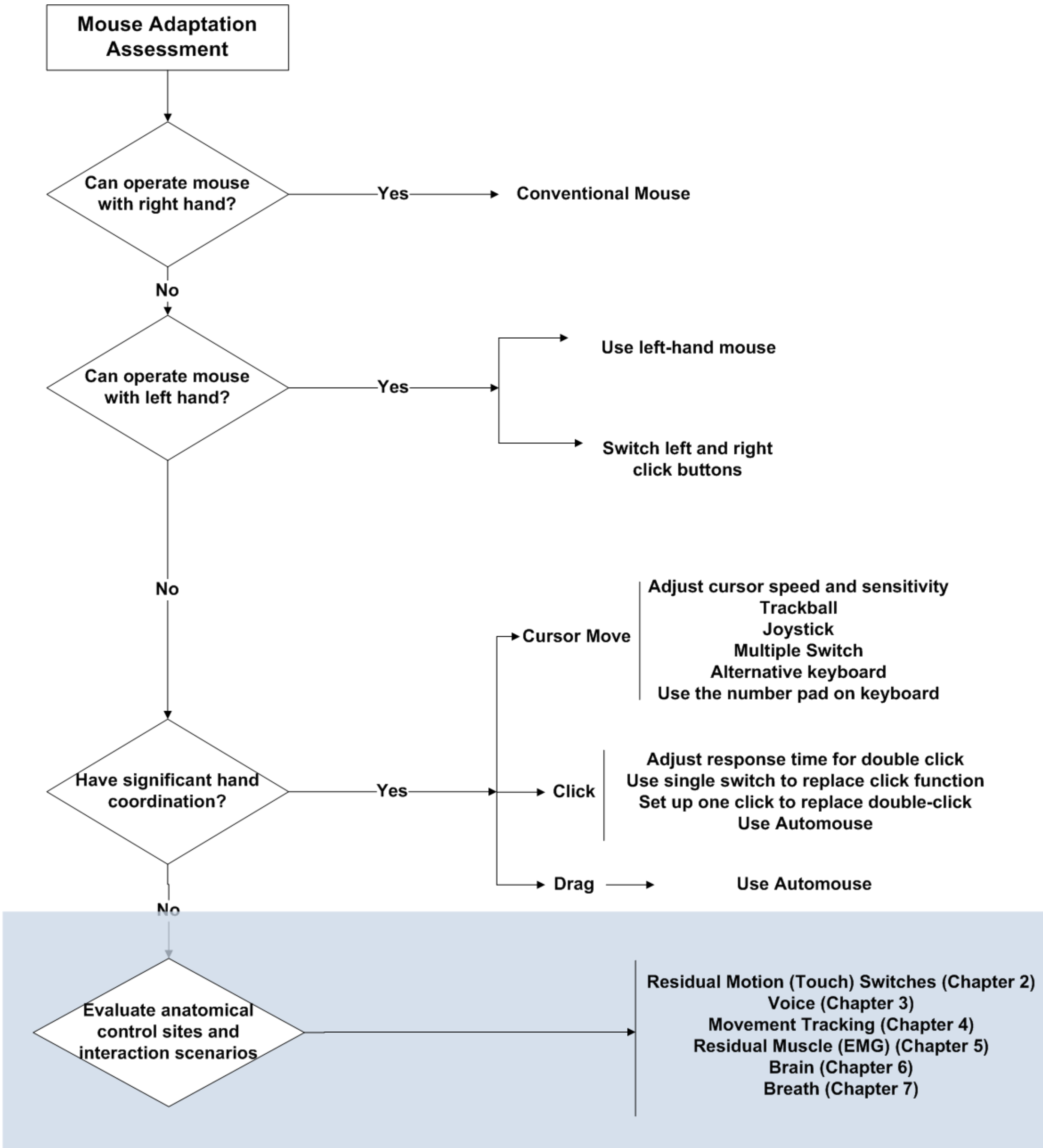


Figure 7: Mouse Assessment Needs (adapted from (Wu et al., 2002))

very serious problem that needs researchers attention, it goes beyond this document's scope. We will only focus on assistive technologies to control a device assuming that the basic physical conditions are already set up. (i.e., the computer is turned on, the switch is within reach,...).

Figure 8: Several action switches

2 Touch Switches, Sticks and Pointers

The switch is a very simple widely used computer access system consisting on an electrical device that the user activates according to its residual movement capacities. Switches are often Yes/No interfaces but this input set can be enlarged with multiple switches (Figure 8). Within a large set of switch-based interfaces we can find different switches operated by hand, tongue, chin, forehead, among others. These interfaces are regularly used with scanning interfaces (the user activates the switch when the desired option is highlighted) although switches can also function as a complementary control mechanism (i.e., perform mouse clicks).

Upper Limb Interfaces

Within tetraplegic patients, we can easily find ones that are able to move one or both upper limbs, although this control may be limited. Moreover, although we can witness the control of the arm (biceps), it is also probable that no full limb control is achieved (triceps, foremarm muscles, flexors and extensors). Looking back to the motor map, these muscle groups are controlled by different nerve roots, therefore a certain lesion degree will affect the muscle control differently, event within a smaller context, as the upper limbs (Table 1). As an example, we can identify cases where the impaired user controls his arm totally but has no forearm or finger control. In this case, the user cannot grab a mouse or joystick, but for instance, he can point or press a button switch. Considering these situations there are several button-press switches and special joysticks, that take advantage from the impaired upper limb residual capacities, whether to emulate mouse movement or mouse clicks, whether to perform selections within a scanning interfacing scheme. There are also several applications tthat use the button switch as an input to a morse code communication system.

As an example, (Shannon et al., 1981) have developed a communication system for

Level	Key Muscles	Related functions
C5	Biceps, Deltoid	Arm/Elbow Flexion, Shoulder Control
C6	Extensor Carpi Radialis	Wrist Extension, Tenodesis
C7	Triceps, Flexor Carpi Radialis	Elbow Extension, Wrist Flexion
C8-T1	Hand intrinsic muscles	Finger Flexion, Hand Grasp

Table 1: Upper extremity function by neurologic level (from (McKinley, 2004))

a non-vocal quadriplegic with motor control only in his right thumb. The system uses the user's thumb movement ability to generate Morse code signals, which in turn operates a personal computer. These signals can therefore be used to write text but also to control other applications.

Mouth and Tongue Interfaces

Even users with high level tetraplegia are prone to have some sort of control in or within their mouth. Although sometimes the impairness can affect inteligible speech, several patients can still move their mouth, clench teeth and move their tongue consistently. Therefore there are some approaches to control electronic devices, whether with a mouthstick, a bite switch or a tongue joystick.

A mouthstick consists of a pointer attached to a mouthpiece (Figure 9). The user grips the mouthpiece between his teeth and moves his head to manipulate control interfaces or other objects. The shaft of the mouthstick can be made from a wooden dowel, a piece of plastic or aluminum (Cook and Hussey, 2002). To control the mouthstick the user is required to have good oral-motor control and the regular use of the mouthstick (i.e. text-entry tasks) is potentially higly fatiguing (Beukelman et al., 1985). However, considering text-entry, it can also be easier to learn than other common alternative communication systems (i.e., Morse Code with sip and puff straw (Chapter 7)) (Levine et al., 1986).

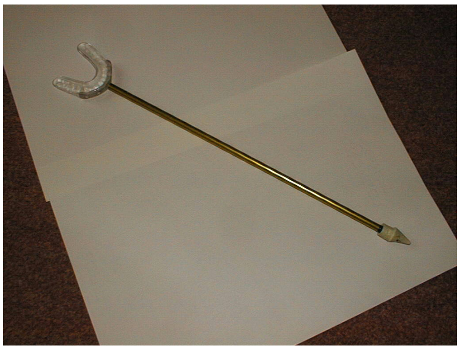


Figure 9: Mouthstick

Within mouth-based switches, sticks and pointers there is a distinctive subarea, the tongue-controlled interfaces that can be argued to be more aesthetic as the user may hide the device inside the mouth. However this approach can also be classified as less hygienic, less ergonomic and harmful to the user. Also, the tongue provides high selectivity as one can easily pick out every single of our 32 teeth (Struijk, 2006).

The Tongue Touch Keypad ™(http://www.newabilities.com/, Last Visited on 30/11/2007) is a comercially available tongue touch system placed in the roof of the user's mouth and operated by the mouth. The system is composed by nine "buttons" that can be configured to control the environment, drive a wheelchair or control the computer.

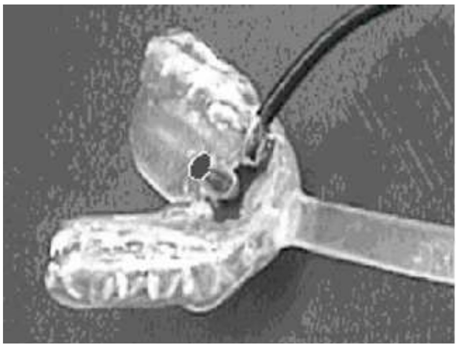


Figure 10: TonguePoint

(Struijk, 2006) presented an inductive tongue-computer interface composed by nine air cored inductors placed on a palatal plate resembling the ones used as dental retainers and an activation unit glued to the tongue. The authors evaluated the system associating each of the coils with a determined alphabet letter and prompting the user for a typing sequence, repeating it about 40 times during three days of measurements, without visual display of the position of the characters. Results presented a a speed of 30-57 characters per minute with a 15-29 % error rate.

Salem and Zhai designed an isometric, tongue operated device, called the Tongue-Point (Salem and Zhai, 1997) aiming at an alternative computer input. As pressure sensitive joysticks have became smaller and effective, is was possible to develop a device operated by the tongue (with its limited movement range). *A Tonguepoint is a mouthpiece that, similar to a dental night or a sports mouth guard, is form fitted to each individual's upper teeth and hard pallet (Figure 10).* Relaxing and speaking while "wearing" the Tonguepoint is possible. Evaluation presented the Tonguepoint at a performance level near to finger isometric pointing.

Other mouth-related type of switches can be pointed like the bite switch that enables a user with good mouth abilities to achieve selection by biting a surface.

Other Head-Based Interfaces

If the user is able to move is head there are several hypothesis to use that movement to offer him with some kind of control. Actually, considering head movement, we can find several comercial devices whether switches, sticks and pointers.

The head pointer (Figure 11) is a physical instrument, similar to the mouthstick, but in this case, the pointer is held by the head instead of the mouth. As the mouthstick, this assitive device helps the user with head motion control to press a keyboard.

Considering wheelchair guidance, it is normal to see the manual joystick replaced by a chin joystick which functions are equal to the hand-operated one, but it is controlled with the chin. Normally the stick is replaced by a ball to ease control and

Figure 11: Head Pointer

to avoid injurying the user.

There are several variations of the above mentioned that can be controlled by the forehead, cheek or teeth.

Discussion on Touch Switches, Sticks and Pointers

Although similar in function the presented approaches are very variable considering the target user, dimensionality and user acceptance. Therefore, besides a general classification there are also differences between the approaches that are also revelead considering the predetermined evaluation criteria:

Potential users range The switch, as sticks or pointers, do not define a particular body part therefore the assistive devices described in this chapter are quite different considering the possible target population. However, one of these devices main advantages is their simplicity and easy adaptation to the user's capabilities. A button switch can be used by a user with hand motion control and a slightly different switch can be used, with the same interfacing scheme, dimensionality and input speed, by a user with head motion control (pressing the button with the cheek, forehead or chin, for example).

Considering the most severe cases where no movement, or enough strong movement, is achieved, the tongue interfaces appear as suitable solutions as even the most severe cases are able to control tongue movements.

Although each solution in this chapter has a determined target group, there are several solutions available that cover the majority of the quadriplegic population.

Dimensionality and Input Speed The simplicity of the presented approach is generally reflected in the solution dimensionality and subsequent low input speed. Particularly, switches have a low communication bandwidth. The stick and pointer solutions (whether by head, mouth or tongue) represent an increase in the selection set and input speed but still have reduced performance.

Accuracy, Robustness and Repeatability In general, the approaches described in this chapter are accurate and robust as they normally depend on direct contact with a certain surface.

Ease of use Upper limb and head solutions are generally easy to use and no major problems have been reported in the surveyed projects and products. Although not naturally used for pointing, the tongue is constantly performing sophisticated motor control for swallow, mastication or vocalization and can therefore be argued as a good control interface. However, in a first approach the user may feel some difficulties. Moreover, if several movements or points are defined there are no mnemonical or visual cues to ease interaction.

Aesthetics, Hygene and Acceptance Tongue approaches have some hygiene, ergonomic and aesthetics issues. While a regular use of the device can harm the user's mouth, the solution aesthetics is prone to be rejected by the user if there are visible components out of the mouth. Also, speech can be difficulted by the mouthpiece. However, if we consider in-mouth wireless solutions, the aesthetics issue disappears.

Mobility Adequacy The solutions surveyed in this chapter are quite independent from the ambient shifts. The only requisite for the majority of switch, stick and pointer-based approaches is the distance between the user and the device as they must be within reach. Thus, whether in a wheelchair, whether in a bed or table, if the device is in an adequate position, control is achieved as solutions are not influenced by illumination, air flows or any electromechanical interference.

Maturity, Availability and Cost Most of the presented solutions or similar ones are commercialized and used by the end-users and generally with low associated costs.

3 Sound-Based Interfaces

A conversational computer, a machine we could sart a conversation with, has always been a dream (Cohen and Oviatt, 1995). The naturalness of speech between humans, its usefulness in eyes/hands busy situations and independence from other motor channels greatly motivated its study as a promising interaction modality. Considering disabled users, speech-based interaction can be truly useful as it maybe the only remaining mean of natural communication left, it requires no physical connection, it has high dimensionality offering maximum degrees of control freedom and it can be adapted to suit the user's needs and scenarios (Noyes and Frankish, 1992; Damper, 1986).

Several severe spinal cord injured individuals detain speech capabilities therefore its use as an input mechanism is potentially advantageous. SCI individuals with lesions below C3 are able to produce inteligible speech being possible users of a speech-based application.

It is also important to notice that speech-based interfaces can go beyhond its inteligibility. Considering a speaker-dependent speech recognition system (trained to a specific user) and its consistent use, the scope of possible users increase as consistent speakers, although not inteligible to other humans, can control applications, satisfying the requirements for the human-computer communication(Noyes and Frankish, 1992).

Speech-Based Interfaces

One of the main advantages of speech input is its high dimensionality. Considering the interfacing schemes classification (Damper, 1986), speech-based interaction is consistent with a direct selection or an encoding scheme, if one wants to reduce its vocabulary. Scanning schemes are not suitable with speech interactions as they are a waste of its dimensionality and degrees of control freedom.

We survey several speech-based assistive technologies across different areas, namely Computer, Wheelchair and Environmental Control. The majority of the presented works try to overcome electromechanical scanning aids with an encoding or direct selection system, aiming at higher performance rates.

Computer Control

The keyboard and mouse pointing devices are still the most used input devices by individuals who are able to achieve their control. It is therefore expectable that alternative interfaces for the disabled try to replace this devices emulating their functionality(Sears et al., 2001), offering the users transparent access to available software. The keyboard with a limited number of possible actions calls for a direct selection or encoded interfacing scheme which suits perfectly with a speech-based interaction as its high dimensionality permits a natural mapping. In contrast, cursor emulation involves a continuous control that is still a challenge when considering speech interaction.

(Dabbagh and Damper, 1985) described two different speech approaches to ease text composition by a motorly disabled user. One of the systems was based in a direct selection of letters and common words while the other is based on an encoding selection of letter-sequences (graphemes). When their work was proposed, speech recognizers were very limited whether in its speaker-dependency whether in vocabulary size. Therefore their major goal was to allow unlimited-vocabulary text composition using a restricted vocabulary. Their first approach is very simple and maps every single character in a keyboard with its "name" enabling the user to select a key by speaking its "name" (i.e., AY, BEE, CEE....). As one may notice, some letter "names" create a confusable vocabulary with low recognition rates. To overcome this problem the users proposed the use of the Pilot's Alphabet (i.e., Alpha, Beta, Charlie,...) which increases the recognition rate but also increases the cognitive load to issue a command. To improve performace, the authors also included some high-frequency words in their vocabulary, which was considered high (70 words) and was therefore structured in several subsets that can be selected. Considering the recognizer's limitations, the authors also developed a system featuring encoded selection and subsequently a smaller vocabulary. The system is based on a matrix of elements where the users select one element by speaking its row and column number. In constrast to previous works where the matrix is composed by single characters, Dabbagh and Damper's work featured a matrix composed by graphemes aiming at higher text composition performances. When comparing their systems, the direct selection scheme performed better although presenting a higher error rate.

Later in 2001, (Su and Chung, 2001) following the same transparent keyboard and mouse emulation principles developed an interface to enable severe handicapped individuals to fully operate a computer. This sytem includes mouse function commands(up, down, left, right, clicking, double-clicking, right clicking and dragging) and, considering a traditional keyoard, other 104 commamds. To reduce the number of possible commands, the authors also adapted a matrix displacement requiring two utterances to select a character. The system is speaker-dependent and the authors state that recognition rates can be higher than 95% in a noisy environment. Considering mouse control, no evaluation was performed that we are aware.

Cursor control is higly problematic when considering speech interaction due to several issues: recognition errors, delays and the mismatch of interaction schemes (Dai et al., 2004). It is generally accepted that speech is not optimal for naturally controlled continuous applications. Therefore, the few projects on cursor control presented in last few years had little or no success. However, there are several speech-based cursor control solutions that seek to overcome these problems and limitations and can be categorized either as target-based or direction-based. A target-based solution is one where the user identifies the desired location, whether a word, an icon, a menu or a region on the screen. As the number of targets increase, target-based solutions become more error-prone. *Problems include users having difficulty remembering the names of the targets, multiple targets having the same name (...), and increased recognition errors as the vocabulary increases* (Dai et al., 2004). Moreover, target-based solutions are not effective to position the cursor anywhere on the screen.

In a direction-based solution the user specifies the direction and distance creating a continuous or discrete movement (i.e., "Move Left two pixels" or "Move Left" followed by a "Stop" to limit the cursor movement). Although better than target-based approaches when considering cursor control, direction based solutions are also limited when the targets are far from the current cursor location and also face some accuracy issues when cursor speed increases due to spoken input delays.

(Karimullah and Sears, 2002) tried to overcome this problem suggesting the use of a predictive cursor, based on known recognition delays that would increase performance and decrease error rates. However, the predictive cursor failed to prove beneficial. (Dai et al., 2004) explored the potential of a grid-based target-based cursor control solution where the user recursively selects a cell until he achieves the desired target with encouraging results.

(Manaris et al., 1999) presented results on a user interface model for providing access to computing devices (mobile or not) through a continuous speech speaker-independent engine. Their system, called SUITEKeys also provides a one-to-one mapping between user utterances and keyboard/mouse operations, *such as pressing/releasing a key and moving a cursor to a certain distance/direction*. To enhance text composition, SUITEKeys provides, besides regular and military alphabet pronunciation, selection of frequently entered words and modelling of task-specific activities (i.e. dialing a number). Moreover, the system includes natural language processing components to improve speech understanding. The authors argue that the system and its inherent interaction scheme is suitable for any kind of computer, whether a personal computer whether a mobile device. The authors claim that *although speech is not the best modality for all human-computer interaction tasks, when delivered at the level of keyboard and mouse it allows for universal access to computing devices* (Manaris et al., 2001).The authors undertook usability studies that showed that their *listening keyboard* is better for users with motor impairments than handstick (37% better), typing rate (74% better) and error rate (63% better). The authors also argue, by transitive reasoning, that, if handstick input is at least as effective as most of the examined alternative inputs devices (the authors compared handstick with stylus "soft keyboards, handwriting recognition systems and telephone keypads), speech input is also at least as effective than alternative input devices, even within a mobile device context (Manaris et al., 2002). However no conclusive results were provided and mobile device usage evolution is continuously rejecting speech input, specially considering its intimacy, subtleness and recognition issues when interacting in public(Costanza et al., 2004).

(Palazzolo et al., 2003) improved the interface to a video game console to enable

Figure 12: Windows Vista Speech Recognizer

its use by a quadriplegic individual. As the joystick was adapted to be controlled by residual shoulder ability, the buttons were controlled by speech, with acceptable delays of 0.5 seconds.

In the last few years, although speech recognition is evolving, there has not been great advances considering computer control. Recent operating systems (i.e., Microsoft Windows Vista) provide speech control capabilities but its use is still reduced, similarly to what we have been witnessing with mobile devices. It is interesting to observe that the recent accessibility package provided by Microsoft in the latest operating system Windows Vista gathers several of the surveyed control approaches, including grid-based mouse control 12.

Wheelchair control

There has been some research on speech wheelchair control which was pioneered by (Youdin et al., 1980). (Mazo et al., 1995) describe a wheelchair developed at the U.A.H (Universidad de Alcalá de Hemares) Electronic Department controlled by voice commands with a set of only eight oral commands relative to eight functions: stop, forward, back, left, right, plus, minus and password. However, the control words attached to this functions are user-dependent and the only condition is that the sounds associated with each function are consistent every time. The "password" function when pronounced stops/starts the recognition of other commands so the user can engage conversations where control words can appear. The response time of the system is of 0.3-0.5 seconds and present a recognition rate of 90% (with maximun noise level of 90dBA). The authors state that the system was "successfuly" tested with disabled users, even with vocalization problems, achieving wheelchair control "in an easy and confortable way".

Although some other voice controlled wheelchairs appeared in the last few years, *voice control has proven difficult to implement within a standard power wheelchair* (Simpson et al., 2002). Safety considerations make fast and accurate responses essential and no speech recognizer can offer this kind of certainty. To deal with this problem (Amori, 1992) limitted the time range of all the commands arguing that momentary commands were less likely to produce collisions or inadequate movements while (Simpson et al., 2002) combine voice control with a set of twelve sonar sensors that identify a safe path of travel. These solution, as others following the same ideas, using Ultra-sound or Infra-red proximity sensors, are yet to be proven as totally complementary to speech towards a secure control.

Environmental Control

In contrast, the tasks involved in control of the domestic environment (with the possible exception of alarms and emergency communications) are essentially non critical in terms of safety. Consequently, unlike wheelchair and manipulator control, the time taken to achieve the desired action is relatively unimportant, so that time required for error correction is freely available. Although some functions (e.g. TV volume control) ideally require proportional control, most actions consist of simply switching appliances on or off. Accordingly, this is a very suitable application within which to assess the potential of ASR (Damper, 1986).

(Damper, 1986) also proposed a voice-based approach to environmental control. The interaction scheme is structured as a two-level encoding selection in which the user identifies the appliance and, in a second phase, the desired action (i.e. <Lights ><off >). The presented approach tries to replace and overcome previous environmental control systems based on scanning schemes and electromechanical switches. The authors state that a direct selection scheme could have been employed (i.e. <lights_off >) but only with more sophisticated word recognition techniques.

Within a restricted scope, (Carvalho et al., 1999) developed a device that allows motorly disabled individuals to control residential temperature using a speaker dependent recognizer with a sated accuracy of over 99%. This system contemplates an extra controller, a sip and puff switch, as well as a mechanical one that works as an emergency switch, if any malfunction occurs.

(Jiang et al., 2000) described a voice-activated environmental control system to aid persons with severe disabilities. The proposed system provides voice control of household electronic applicances through *via the X10 protocol transmitted through both a radio frequency channel and household electrical wires*. The recognizer handles 20 different phrases each of them with 1.92s in length. The user must pause between the words spoken. Jiang et al.'s system is advantageous over other voice recognition approaches due to its low cost: it is based in a voice recognition chip, dismissing the need por a PC or a laptop. Also, the size and lightweight of the system make it really portable.

Non-Verbal Voice Interfaces

(Igarashi and Hughes, 2001) state that *traditional speech recognition interfaces are*

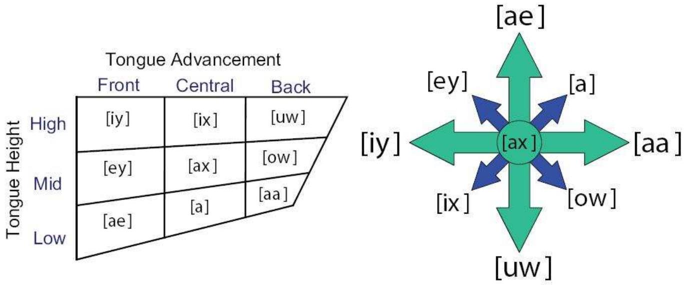


Figure 13: Vocal Joystick Configuration

based on an indirect conversational model. Although the authors think that speech interaction is suitable for tasks like flight reservations, they also argue that an approach to handle more direct interaction is required. Igarashi and Hughes proposed the use of non-verbal features in speech like pitch, volume and continuation to control interactive applications.

(Olwal and Feiner, 2005) also use prosodic features of speech as rate, duration and volume, as well as audio localization to control interactive applications. The authors developed a speech-based cursor control system using non-verbal features and the user's position. In the first approach the user controls the direction by issuing speech commands (left, right, up, down) and controls the cursor speed with the speech rate. In a second approach, the user controls direction by leaning to the left or right (audio localization). The two approaches can be used together. Object manipulation (i.e. Rotation) was also experimented.

The Vocal Joystick (VJ) (Bilmes et al., 2006) makes use of vocal parameters to control objects on a computer screen (buttons, sliders, etc..) as well as controlling mouse movement. This system goes beyond the capabilities of sequences of discreet speech sounds and explores other vocal characteristics such as pitch, vowel quality, and loudness which are mapped to continuous control parameters. Although several characteristics are to be explored, actually the authors extract *energy, pitch and vowel quality,* yielding four simultaneous degrees of freedom. Localized acoustic energy is used by VJ mouse application to control the velocity of the movement as vowel quality is used to select directions (Figure 13). The authors rely on vowels' high energy and suitability for environments where both high-accuracy and noise robustness are crucial and state, sustained with a comparison evaluation, that the Vocal Joystick competes with Eye-Tracking pointing devices and for some tasks it's an improvement over those.

Presenting the same motivation as Vocal Joystick and considering speech recognition flaws, Sporka et al. (Sporka et al., 2006) developed a system for controlling the mouse pointer using non-verbal sounds such as whistling or humming. This can be done in two modes: orthogonal, where the pointer, based on the initial pitch, is moved either horizontally or vertically, varying speed accordingly to the difference

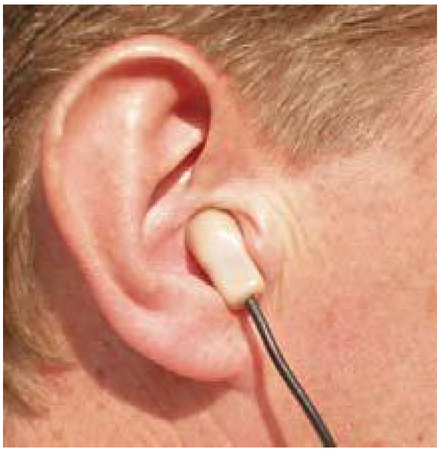


Figure 14: Earplug

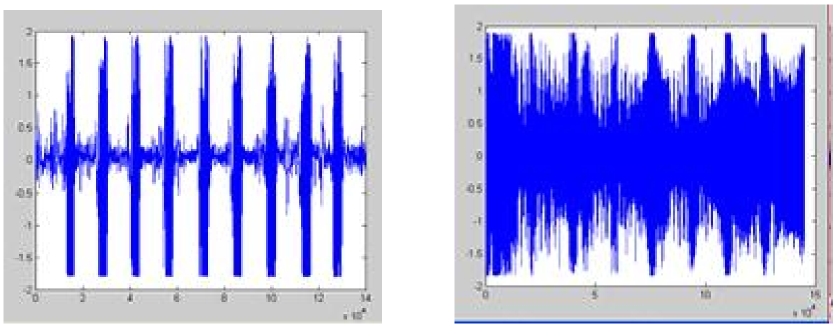
between current and initial pitch; and melodic mode, where the cursor moves in any direction with a fixed velocity (or idle). The direction of motion is dependent on the pitch of the tone. Left button click is emulated in both modes through a short tone. Users prefer the *orthogonal* mode because it is easier to operate and *humming* because it is less tiring than *whistling*.

Aural Flow Monitoring Interfaces

An interface capable of controlling devices in response to tongue movements and/or speech using the unique properties of the human ear as an accoustic device was presented by (Vaidyanathan et al., 2006; Vaidyanathan et al., 2007). This bi-modal interface makes use of changes in air pressure and sound waves (vibrations) in the ear to control a powered wheelchair. The authors rely on the fact that particular movements of the tongue and speech produce traceable pressure waves with strength corresponding to the direction, speed and/or intensity of the action. These waves are collected with a microphone, similar to a earplug hearing device, introduced in the user's ear (Figure 14).

One of the great advantages of the system when compared to traditional speech-recognition devices is the enormous noise reduction as no external activity is gathered (Figure 15). The authors defined four tongue movements and seven monosyllabic words (up, down, left, right, move, kill, pan) and tested both modalities. Tongue movements were tested with four subjects with a mean accuracy of 96% while speech was tested with three subjects with an accuracy of 95.87%. Tongue movements were observed to be faster, quieter and easier to the user for direct motion device control. On the other hand, speech requires less calibration and training and has higher dimensionality. Although very promising, we are still not sure about the scalability of the system considering the number of commands and word length.

However, a commercial version of this interface has already been presented offering disabled individuals the ability to control a powered wheelchair (Think-a-Move,



(a) Sensor in the ear (b) Sensor in front of the mouth

Figure 15: Speech data, 9 trials to the word "one", high noise environment

Ltd., http://www.think-a-move.com/, Last Visited on 28/11/2007).

Using a similar setup (ear microphone), (Kuzume and Morimoto, 2006) research the tooth-touch sound as an input mechanism. The authors analyze the tooth-touch sound characteristics (amplitude, central frequency, period between sounds, duration), using a bone conduction microphone, which can be placed, if stable, anywhere in the head. Two approaches were discussed: ear microhpone or an headset. The authors selected the ear microphone, gathering vibrations in the auditory canal. The solution is argued as suitable to Environmental Control System although no usability studies were performed. Moreover, the prototype still insufficiently suppresses body movement noise.

Discussion on Sound Interaction

Besides the works presented, in the last few years we have witnesses the spreading of speech recognition devices both in personal computers and mobile devices. However, although the technology is widely available, its use is still reduced, mostly due to social constraints and low recognition levels in noisy environments (Gamboa et al., 2007). This fact is also true for disabled users. Considering the technology characteristics and the study of its application as an assistive technology we can now analyze its advantages and disadvantages on the pre-determined focus points:

Potential users range Individuals with lesions above C3 typically lose diaphragm function and require a ventilator to breathe. This impairment can therefore make difficult or impossible for the impaired user to communicate. However, speaker-dependent recognizers can deal with speech that although not intelligible, is consistent, increasing the scope of possible users. On the other hand, it is important to consider that even below C3 lesions can, and normally do so, damage breathing function and reduce voice strength, hence limiting the interaction, specially considering the distance to a microphone.

Dimensionality and Input Speed One of the main advantages of speech input is its high signal dimensionality: assuming the user has normal speech, the number of possible issued commands is limited only by the size of vocabulary the recogniser can handle without an unacceptably high error rate. Thus, use of speech will often enable an electromechanical scanning aid to be replaced with an encoding or direct selection system. (Damper, 1986)

Accuracy, Robustness and Repeatability Although research in this area has been active for many decades, robustness is still a key issue that should be considered. Despite significant research efforts in automatic speech recognition, existing ASR systems are still not perfectly robust to a variety of speaking conditions, noise and accented speakers, and they have not yet been universally adopted as a dominant human-computer interface (Bilmes et al., 2006). Noise is still a problem, but using a short command structure with a specific word as pre-command string it is possible to reduce enormously the noise effects. Indeed, ASR to date is very sensitive to variations in the channel (desktop microphone, telephone handset, speakerphone, cellular, etc.), environment (non-stationary noise sources such as speech babble, reverberation in closed spaces such as a car, multi-speaker environments, etc.), and style of speech. A typical approach for achieving robustness of environment focuses on obtaining a clean signal through a head-mounted or hand-held directional microphone. However, this is neither tether-free nor hands-free, and it makes speech-based interfaces very unnatural. Moving the speech source away from the microphone can degrade the speech recognition performance due to the contamination of the speech signal by other extraneous sound sources (Carpi and de Rossi, 2006).

Interfaces based on aural flow monitoring, although recent are very promising as a new communication and control concept. An extended evaluation is required but preliminary results are encouraging.

Ease of use Speech can be argued to be a natural form of communication. However, although spoken language is effective for human-human interaction it often has severe limitations when applied to human-computer interaction (Shneiderman, 2000). The supposed interaction naturalty can possibly be translated in inappropriate expectations by the user (Damper, 1986) which results in a lack of interaction consistency, required for human-computer communication. Also, considering cognitive load, it is harder for an individual to speak and solve a tough problem, as the activity is handled in the same part of the brain, than to control a mechanical switch and think ate the same time (Shneiderman, 2000).

Another limitation on speech interaction is its inadequacy to direct low-level controls, such as scrolling. Continuous interaction as well as any WIMP-based interaction is difficult to cope with speech interfaces (Igarashi and Hughes, 2001). However the non-vocal parameters introduced by (Igarashi and Hughes, 2001) can diminish this problem and improve continuous interaction.

Setting up a voice based system has no difficulties which can be a great advantage for the impaired user and caretakers.

Aesthetics, Hygene and Acceptance Considering aesthetics and hygene, speech-based interaction is an optimal choice. There is no contact between the hardware and the user and due to microphone size and its availability in any regular mobile device it can be totally unnoticeable.

On the other hand, user and social acceptance is compromised. Privacy concerns arise and it is almost impossible to accept voice-based interfaces as suitable for public interaction. It is worth noting here that even sub-vocal recognition systems are currently under development. They use wearable myographic sensors to collect nerve signals transmitted from the brain to the vocal cords when the subject "reads silently to himself". The sensors detect the nerve signals that generate this sub-vocal speech and relay those to a computer program. Applications of this technology include improved voice recognition systems, systems allowing the transmission of vocal commands in noisy environments (Manabe et al., 2003; Jorgensen and Binsted, 2005).

Mobility Adequacy Speech-based interaction offers the promise of greater user mobility. This is true for an indoor enviorment with a personal computer and a fixed microphone as for an outdoor environment, using a mobile device.

Maturity, Availability and Cost Research in this area has been active for many decades. These efforts culminated with the appearance of voice recnognizers in the majority of mobile devices as well as in the latest operating systems. The hardware required is also highly available presenting low costs (Noyes and Frankish, 1992).

4 Gaze and Motion Tracking Interfaces

There have been several approaches to control electronic devices, specially the mouse and throught it other applications, whether by head movements, eye movements or other body movements with less population coverage but wider control capabilities. These approaches are different in the operating principle and can vary considering the technique (i.e., Electrooculography, Optical pointers, Infra-red Reflectance, Video Appearance ,..). It is importante to notice that Eye tracking is the process of measuring either the point of gaze ("where we are looking") or the motion of an eye relative to the head.

All of the approaches try to use more information, whether from the visual line of gaze whether by head direction or other body part, to enrich the dialogue between the user and the computer(Jacob, 1993; Jacob and Karn, 2003). Although with the same purpose, the interfaces surveyed in this chapter are quite different and go from electromechanical approaches (electrooculography) to video appearance based interfaces.

Electrooculography

Electrooculography (EOG) is a technique for measuring the resting potential of the retina. The resulting signal is called the electrooculogram. The main applications are in ophthalmological diagnosis and in recording eye movements.

Deliberate eye control actions can convey useful information in basically two independent ways: through the six extra-ocular muscles by absolute eye position, speed and direction of movement, or through the levator palpebrae (eyelid) and other periorbital muscles as unilateral or bilateral blinking and blink duration (Shaviv, 2002).

Usually, pairs of electrodes are placed either above and below the eye or to the left and right of the eye. If the eye is moved from the center position towards one electrode, this electrode "sees" the positive side of the retina and the opposite electrode "sees" the negative side of the retina. Consequently, a potential difference occurs between the electrodes. Assuming that the resting potential is constant, the recorded potential is a measure for the eye position.

The ability to detect eye movements through head-mounted electrodes lead to the appearance of EOG device control interfaces. This approach is very interesting considering that it's less expensive than reflectance eye-tracking interfaces and doesn't require a determined steady position as most tracking approaches imply. The drawbacks of EOG-based interfaces are mainly aesthetic (Figure 16), although there are other disadvantages like the lack of accuracy on some eye-movements detection.

Like the tracking systems it suits for persons with eye-control only. Similarly to other presented techniques, we survey relevant EOG-based projects mainly considering computer, wheelchair and ambient control.

Figure 16: Example of Electrooculographical Interface

Computer Control

In 1990, (LaCourse and Hludik, 1990) presented DECS, discrete electrooculographic control system, a communication tool for persons with disabilities. As with other eye-movement based techniques, the authors justify the need for DECS with the slow response times and motor coordination required for the adaptive switches and scanning devices available. DECS relies on small eye movements both in horizontal and vertical directions. *A target is selected by staring at it for a preset length of time.* LaCourse and Hludik argue that DECS is a potential input for wheelchair, environmental, computer and communication devices control. On the other hand, the authors focused their efforts on the accuracy of the system and no practical results in those interaction scopes were presented. The cost of the system is stressed as a particularly interesting characteristic as the difference compared to IR Eye-Tracking devices is huge. Although IR systems are becoming cheaper, the difference is still substantial.

(Kaufman et al., 1993) also present an EOG interface stating it as an inexpensive and non-intrusive system. The system detects eye movement but also *eye-gestures*, such as left and right winking, blinking and types of movements (sacade, smooth pursuit). Users tests on menu selection (3*2 boxed menu, two-level menu) were performed with two experienced users achieving a 73% accuracy rate on menu selection. The authors state that the error rate is mostly related with heand and muscle movement interface, signal drift, and channel cross-talk. However, they also argue that considering applications where a rough resolution is used, such as driving a wheelchair (ex: forward, left, right, stop), head movements are negligible. Although it is true that reducing the possible actions also reduces the error rate, one must consider that an interface to drive a wheelchair requires high certainty and accuracy rates.

EagleEyes (Gips et al., 1996) is an electrodes-based device developed at Boston College that measures oculographic activity through five surface electrodes placed on the head. Using EagleEyes, the users are able to run educational and entertainment software, spell out messages and navigate through the Internet just by moving their eyes. The system is composed of two battery-powered boxes, one for the amplifiers and one for the digital logic. The system was installed in the Boston College Campus School, a day-time educational facility for multiple impaired students ranging from three to twenty-two, to augment the student's communication and expressivness capabilities. To use the system, each student has to acquire the skill control. The authors state that people with severe disabilities the syste can take from 15 minutes to many months to acquire the required eye control skill. Mouse control, painting and a shooting video game application are used in the learning phase. After achieving control, the student will be able to use the system to create words and sentences, answer multiple-choice quizzes or read the text on lessons according to the student's gaze direction.

Several EOG control systems rely on direct mapping between the eye and cursor position. However, these systems must incorporate sophisticated instrumentation and software to null out the DC artifact always present due to variations in skin thickness, skin conductivity, eectrode placement and electrode gel drying. Also, the direct mapping systems need complex calibration procedures to assure the correct alignment with the eye direction and cursor position. The Eye Mouse (Norris and Wilson, 1997) overcomes the unreability and cost stated above with a joystick-similar approach. Therefore, if the user wants to move the cursor in a certain direction it is only required that he diverts his gaze 30^{o} in that direction for half a second. The cursor continues the movement until the user blinks twice. Once it is stopped, two blinks will produce a single-click while three blinks will produce a double-click. Single blinks are ignored as they are commonly unintencional.

One of the most relevant disadvantages on electrooculography is the baseline drift that obscures eye-movement signal. To overcome this issue (Patmore and Knapp, 1998) investigated the use of the electrooculogram and visual evoked potentials (VEP) (Chapter 6). The authors use a two-phase approach to detect and cancel EOG drift where the first level uses the EOG signal first and second derivatives to measure drift and VEP to discriminate between static eye gaze and moving eye gaze. Thus, the computer cursor, presents a flashing stimulus causing a high response when the gaze is directioned at the pointer location and a null or soft response when the alignment is lost. When the system is misaligned with the user's gaze, a reacquisition algorithm is employed.

Another major issues concerning EOG-based interfaces is the neccessary awkward setup prone to be rejected by the user but also, due to the setup complexity, the error rate increase related to electrodes slippage. (Kwon and Kim, 1999) developed an EOG-based mouse focusing on user's convenience. Thus, the electrodes are positioned in five particular points on a glasses frame assuring good contact and requiring no electrolyte gel. Also, the authors use a microcontroller that estimates direction, amplitude, detects blinks and communicates the estimated information with a Personal computer via wireless (Radio Frequency). The authors state that the users can control several Windows functions and play Tetris (right, left, up,

Figure 17: Headphone EOG interface

down) after a brief training session (a few minutes).

(Manabe and Fukumoto, 2006) developed a headphone-type gaze detector which relies on the analysis of multiple EOG channels measured at the location of headphone cushions 17. The authors aim at a full time wearable interface, easy to wear, easy to use and that can be available whenever desired. The proposed system eliminates common EOG issues like cosmetic acceptability and user's field of view limitation but other problems arise: low Signal-to-Noise ratio as the electrodes are far from the signal source; separation between vertical and horizontal components as, in opposite to traditional approaches where the electrodes are placed above and below and right and left, the electrodes are placed near the ears. The authors use a Kalman filter to to estimate gaze direction and achieved an overall estimation error of 4.4º (horizontal) and 8.3º (vertical). Although still a work in progress, the proposed system promises to resolve some of the EOG major drawbacks augmenting its suitability to interface control, even when in public.

Wheelchair Guidance

(Barea et al., 2002) implemented a wheelchair guidance system based on electrooculography. It consists of an electric wheelchair with an on-board computer, sensors and a graphical user interface. Besides studying an eye position model with good accuracy (less than 2º), the authors devoted some effort on wheelchair guidance strategies developing three different interfaces: direct access guidance, guidance by automatic or semi-automatic scanning techniques and guidance by eye commands. Considering direct access guidance, the user controls the wheelchair by positioning a given cursor over the desired action button displayed on the graphical user interface and then validating his action. The authors are aware of the problems underlying this approach namely, the fact that the human eye is always on therefore prone to issue undesirable commands but also that the screen has to be in the user line of sight thus limiting visibility (this problem achieves greater significance considering users that cannot move their head). The scanning guidance mechanism is aimed at users with little precision in their eye movements and it is based in a screwn showing several commands that are scanned, whether automatically or semi-automatically, and can be selected by an action or only a given period of time. It is important to notice that although not requiring a precise aim at a target this approach still requires the user to look at the graphical interface limiting the guidance. The authors developed a third method, guidance by eye commands, that maps some eye movements as commands. Therefore, the user no longer needs to select an action within the graphical user interface. Although no extra display is required, this method still detains some problems as the user involuntarly movements can be misjudged as commands and, on the other hand, a correct manipulation of the system certainly restricts the user "looking freedom".

Overall, eye-movement wheelchair guidance has several obstacles regarding involuntarly movements and safety but also voluntarly movements as the user still needs to see the surrounding environment.

Head Optical Pointers

An Head Optical Pointer is a device similar to the physical head pointing device (Chapter 2) but in this case the headpointer detects the raster scan of the computer display and calculates the position at which the user is pointing, similar to a lightpen (Hamann et al., 1990). Therefore, the physical interface is replaced by a beam (normally infrared or near infrared light). For instance, (Vanderheiden and Smith, 1989) present an approach where a keyboard image is displayed on one television screen and selection is realized through a long range optical pointer while the normal computer output is displayed on a second screen.

People with good head control can use an head pointing device to move a cursor on the screen or to point at a surface with photodetectors (i.e., a special keyboard). On the other hand, mouse selections can be made using an external switch (i.e., sip-puff switch). However this fusion is error prone as the extra effort to activate the switch often causes the head to move.

As an example, *Lomak (Light Operated Mouse and Keyboard) is an input system that uses a light pointer affixed to the user's head or hand (Figure 18)*. Data is entered into the computer by aiming the light beam at the accompanying keyboard's rotary-style letter and number pads (http://www.lomakkeyboard.com/products/Lomak.html, Last Visited 28/11/2007).

(Chen et al., 2007) presented an infrared-based home appliances control consisted on a infrared and low power laser transmitter mounted onto the eyeglasses and a board with infrared receivers (Figure 19). The system is focused at users with

Figure 18: Light Operated Mouse and Keyboard

neck rotation movements and enables them to operate several home appliances by pointing at the desired "device" and selecting, using a puff switch to turn the IR emitter on and off.

Within these systems and on gaze-tracking applications, simple pause or dwell time is a common technique to emulate single mouse click (i.e., select characters in an on-screen keyboard.). To accomplish a certain selection, the user holds the pointer over a target for a predetermined amount of time. Other actions (like double-click, left-click and drag) are commonly achieved by selecting the mode in a configuration area. This method enables the users to fully achieve mouse emulation control although requiring several extra configuration movements (change between modes) and pause intervals.

(Hamann et al., 1990) propose a switchless selection approach based on head gestures (nod and shake) where several intentions are differentiated through a combination of pauses, head nods and head shakes. It expands the simple pause and button-based configuration to improve performance. Multi-level pauses are used to differentiate several single button actions as head movements are used to emulate other buttons and to accelerate selections. Preliminary results present the system as usable by the disabled. However, the complexity of the multi-level approach causes some confusion and the state feedback mechanisms should be further studied.

Reflectance-Based Tracking

Tracking the user's eyes and/or face has long been a research issue as this information can be useful within several scenarios. While gaze-trackers present large costs to the normal user, other approaches, less expensive have been proposed. Therefore, although we can find some research projects and comercially available

Figure 19: Infra-red home appliance control system

gaze-trackers they are mostly used within companies, namely to perform usability studies. However, some approaches rely on the same reflective principle, where a surface is iluminated with infra-red light and the desired position is tracked using the reflection surface. In this section we survey some projects and products both on head tracking (using an additional reflection surface) and gaze-tracking (using the eye reflection characteristics).

Head Tracking

One reflective approach to track the user's head requires him to wear a small, reflective target on his forehead or on a pair of glasses. In these kind of systems, the camera includes an illummination (infrared or near-infrared light) module targeted at the user's face. The approach is signficantly easier and lighter considering processing as the camera only has to track the reflective dot. Also, the reflective dot is a small overhead as it is barely noticeable.

The HeadMouse from Origin Instruments and Tracker are comercial examples of reflective head tracking devices (Figure 20) .

Gaze-Tracking

Gaze-tracking interfaces consist on a camera focused on one or both eyes. Most modern eye-trackers use contrast to locate the center of the pupil and use infrared and near-infrared light to create a corneal reflection (the video image is analyzed to identify a large bright circle (pupil) and a brighter dot (corneal reflection) and compute the center of each: the line of gaze is determined by these two points). Depending on initial calibration, the vector between these two features can be used to compute gaze intersection.

(a) Head Mouse™ (b) Reflectance dot (c) Tracker™

Figure 20: Infrared Reflectance Tracking Devices

Gaze tracking setups vary greatly; some are head-mounted, some require the head to be stable (for example, with a chin rest), and some function remotely and automatically track the head during motion.

The ability to track gaze direction has been used in several areas (Neuroscience, Psycohology, Marketing, Advertising, Human-Computer Interaction) and, as interactive systems are concerned, there are two main subareas: selective and gaze-contingent. While selective systems use gaze direction as a direct pointing device (emulating the mouse), gaze-contingent systems use gaze knowledge to facilitate rapid rendering of graphic displays (Duchowski, 2002).

A recent and one of the most popular comecial eye-tracking systems is MyTobii P10 (http://www.tobii.com/, Last Visited on 29/11/2007). This system is a portable eye-controlled communication device. Instead of an independent tracking system, MyTobii is an integrated unit, composed by a 15" screen, eye control device and computer (Figure 21). The authors argue that it can be used in a desk, wheelchair, bed and it is robust to large head movements, glasses use, eye color or light conditions. There are other similar approaches like Erica Eye Tracker (http://www.eyeresponse.com/Disabilities/, Last Visited 29/11/2007), which can be bought with several additional products from keyboard emulators to environmental control appliances. The packages developed can therefore offer the user several devices' control, which augments the system success.

In opposite to traditional IR detectors that explore both eye-wink and eye-position, The Eye Wink Control Interface (EWCI) relies only on eye winks therefore excusing sacrificing head motion or speech (Shaw et al., 1990). The system enables device control through eye winks of varying durations. The system is based on an IR emissor/detector combination both clamped on the earpiece of a normal pair of eyeglass frames (Figure 22). When the lid is closed the reflection will be weaker (more absorbant than the sclera) thus a threshold can be established between open/closed states. Although possible wink durations can be established, the authors presented a simple approach with 4 states where each eye can be winked, both can be opened or both simultaneously winked (reflexive winks are excluded considering the wink time). User evaluations on maze navigation with fully-capable individuals showed that the users were capable of issuing commands and remembering control sequences while still able to move their head and speak.

Appearance-Based Tracking

Although reflectance-based techniques take advantage of the eye and gaze direction, most of the solutions still require wearing extra instruments, such as infrared appliances, headset with cameras among others. Also, Infrared-based devices are generally expensive. Thus, thanks to the advances in the field of face recognition and computer hardware, appearance-based techniques have appeared in the last few years. These are characterized by the use of simple USB cameras that track a predetermined feature in the user's body (normally the face) (Chen, 2003).

Face Tracking

The CameraMouse (Gips et al., 2000) tracks selected body features (i.e., nose, lips, eyes, finger, foot) with a video camera and uses the seelcted feature to directly control the mouse pointer on a computer (Betke et al., 2002). Selection are based on "dwell time". Several features are available to be chosen which offers a great generability considering target users. Also, the system requires no calibration (just feature selection) nor any body attachments which extends its usability and user acceptance.The authors evaluated the system with both fully-capable (20 users) and disabled individuals (12 users). While 10 of the disabled were Cerebral Palsy patients, two were Traumatic brain injuried: one of them did not have enough muscle control to use the Camera Mouse (uses EagleEyes EOG System) while the other was capable to spell a sentence and continued to use the system after evaluation.

Face tracking interfaces face several problems namely regarding position and ori-

Figure 21: My Tobii P10 ™

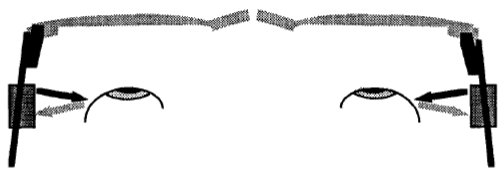


Figure 22: Eye Wink Control Interface

entation shifts, lightning variations as well as complex backgrounds. (Chen, 2003) present a real-time face recognition approach focusing on robustness considering the refereed issues. The system uses a simple USB digital camera and uses eye and lip position as mouse control features. The authors included several filtering and estimation modules to cope with user position shifts, lightining variations and complex backgrounds (including other persons). The authors argue that the system is not too greedy (around 40% on Microsoft Windows system on a Pentium 4 1.0GHz CPU) and works *with roughly 10% wrong decisions.*

Considering the precision required for direct *what I look is what I want* paradigm and the possible lack of ability within the target population to aim at a target, (Perini et al., 2006) developed the Face Mouse, an appearance-based tracking interface that uses a derivative paradigm ("*where I look is where I want to go*"). Hence, the user can interact with the computer even if his movements are spastic or not precise. (Perini et al., 2006) use a semi-automatic feature selection as this task is performed by an operator, trying to eliminate the reduced robustness directy connected with automatic feature selection methods. The nose tip is argued as a good feature and the interaction is realized through a 3x3 grid-based interface, which size can be adapted considering the user's difficulties and capabilities. The presented interface can be used to control house appliances, writing and control general Microsoft Windows applications. Face Mouse has been tested with 10 tetraplegic users. The evaluation consisted in writing a sentence both with FaceMouse (with a prior 8-10 hours training phase) and their habitual writing mechanism (Scansion - a scanning system with single-switch input). Face Mouse outperformed Scansion system with a speed up of 59% with an extra speed up of 25% when using dynamic acceleration, achieving a mean result of 13.5 characters/min. The system works in a regular PC with a USB digital camera, consuming 50% CPU time.

The Facial Mouse (Granollers et al., 2006) is a user-independent mouse emulator system also based on the user facial movement, using a regular USB camera. However, besides dwell clicks (automatic click after stopping the pointer), the user can generate mouse clicks through sound emission or even by using an external click .

Pointing, Gesture and Motion Tracking

Besides face and head-tracking approaches, there are other vision-based approaches that explore other possible residual capabilities. For example, users with upper limb

Figure 23: Soft Remote Control System

function can point at a certain target or issue a command through some predetermined gesture. Also, the capacity to move or occlude objects can be used to replace touch switches, alternative mice and joysticks.

(Granollers et al., 2006) presented the WebColor Detector, a software package able to detect in real-time the presence or absence of a distinctive color and to track its position. This project focus on the emulation of switch, joystick and mouse functions through the manipulation of color markers (requires previous colour selection) attached to a surface or the user's body. The switch functionality is very simple and can be performed whether by using a static marker where the user has to cover or uncover the marker when he wants to perform the action, whether by using a dynamic marker where the user must move a body part that has mobility (with the sticked marker) until it appears or disappears in the image. Mouse movement emulation is performed using the dynamic marker approach as moving the marker also moves the pointer in the screen while mouse click can be performed with dwell click technique. To emulate a joytick a 3x3 matrix is presented in the video window. Each cell represents a direction and the central cell represents the click. This matrix can be matched with a physical version of a paper to ease marker placement. A qualitive analysis on the user evaluation presented the WebColor Detector as a good joystick and swith emulator but poor as a mouse emulator when compared with the Facial Mouse, a face tracking approach.

(Do et al., 2005) developed a soft control system for the "Intelligent Sweet Home" where the user points at the device he wants to control and commands the device using predefined hand gestures and hand motions (Figure 23). Although the system requires large upper limb capabilities, the gestures can be personalized and suited to the user's abilities. The system is composed by three ceiling mounted zoom color cameras targeted at the user. Evaluation showed high recognition rates (95.7% with hand motion and 80.7% with both hand motion and hand posture).

Inertial sensing is another method to retrieve information on user movements. Therefore, an accelerometer can be placed on a body area the user has control of and use the movement as a command launcher. (Chen, 2001) designed another head-operated mouse but employing two tilt-sensors placed in a headset to determine head position. As one tilt sensor detects lateral head motion (left-right displacement), the other detects head's vertical motion (up-down displacement). To ensure mouse function completeness a touch switch was included to perform single clicks. The system communicates with the computer through Radio Frequency. The system was evaluated with six quadriplegic patients with about 95.1% accuracy.

Ultrasound Interfaces

Ultrasound technology was originally developed as sonar to track submarines during World War I. It was first used medically in the 1950s and it is considered very safe. It is a cyclic sound pressure with a frequency greater than the upper limit of human hearing. It is typically used to penetrate a medium and measure the reflection signature or supply focused energy. The reflection signature can reveal details about the inner structure of the medium. The most well known application of this technique is its use in sonography to produce pictures of fetuses in the human womb.

Non-contact Ultrasound

Considering human-computer interaction, the ultrasound can also be used as a tracking mechanism. Actually, if one has a receiver and a transmitter, the distance between them can be estimated, if the ultrasound is regularly emitted.

The HeadMaster Plus™is a device similar to the IR reflectance based approaches (i.e., HeadMaster™) but instead of the reflection dot, the user wears a headset with three ultrasound receivers while an emitter is placed above the computer screen. Head orientation is determined according to the distance gathered in the three receivers. The computer cursor is moved across the screen as the user turns his or her head up, down, left, or right.

Researchers at the Palo Alto VA and Stanford University have developed a device to control wheelchair movement by head position. Two ultrasonic sensors monitor head position, and other sensors detect obstacles and walls to the side. In operation, the user controls forward movement and turns by moving his or her head in the corresponding direction. Obstacles are auto matically avoided. A "cruise control" feature is incorporated, and in the automatic mode the chair can travel parallel to a wall or other guide without user intervention (Jaffe, 1982).

The Ultrasonic Head Controller Unit (UHCU) is the result of research and development conducted at the Palo Alto VA Rehabilitation Research and Development Center and, unlike switches or joysticks, provides a non-contact control system for severly disabled individuals. The Ultrasonic Head Controller Wheelchair (UHCW) is an adaptation of UHCU to a wheelchair and its latest generation is composed by two ultrasound transducers and an on-off switch located in head rest. The users tilts his head off the neutral vertical axis to control the movement direction. The system was improved and tested over a cumulative period of 14 months. The users reported the system advantages (*Better all around visibility, non-contact components and hands-free operation with less fatigue*) but also its disadvantages (*Assistance* *of caregiver always required, set-up and adjustments difficult and position of on-off switch impossible for kyphothic [1] subjects*) (Ford and Sheredos, 1995).

(E. D. Coyle and Stewart, 1998), motivated by the research undertaken by (Jaffe, 1982), investigated several hardware and software adaptations to improve the ultrasound control unit. Their system is composed by two sets of piezoelectric ultrasonic transmit/receive transducers placed on a mounting frame to the side and the rear of the user's head. The system uses a trignonometric algorithm to determine head position using the reflected signals from the user's head. The authors researched the ultrasound control unit as input for keyboard typing and mouse emulation. Also, the authors studied a particular Graphical User Interface system, a Telephone Pad, which enables motorly disabled individuals to work as telephone operators but also to use it within their personal interests (communication, help mechanism).

Contact Ultrasound

(Lukaszewicz, 2003) present an approach based on the recognition of ultrasound images obtained from the bottom part of the chin to keep track of the tongue movement. Although the authors aim at speech recognition for the mute, the early results are quite limited to that purpose but, on the other hand, suitable for wheelchair control or mouse emulation. Moreover, the authors presented results where eight tongue movements can be distinguished. (Huo et al., 2007) presented a similar system but instead of ultrasound technology, a magnetic tongue tracking is performed but in this case a permanent magnet must be placed in the tongue while sensors must be placed outside of the mouth (the authors used a baseball helmet).

Although the system may seem promising, the cost of a medical ultrasound imaging device difficults its commercial availability.

Discussion on Gaze and Motion Tracking

Tracking residual movement on the user's body (including eye movement) is a widespread computer access approach. There are several comercial products across the several areas surveyed in this chapter. We analyze their main advantages and disadvantages considering:

Potential users range The target group for eye-based interaction is quite large. Actually, besides brain control, eye-based interfaces are one of the approaches that gather a wider number of possible users as only eye-control is required. Therefore, even individuals with C1/C2 impairments are possible users of the system, whether using simple eye-wink interfaces (if capable of winking) or eye-mouse control interfaces (if capable of full eye motion). However, although the majority of spinal cord injured users is a gaze-tracking possible user, some-

[1] Kyphotic is an abnormal rearward curvature of the spine, resulting in protuberance of the upper back, normally called a hunchback.

times that is only possible with some extra aid mechanisms like a chin rest to guarantee stability. Naturally, approaches based on head motion require an higher control degree (below C3 impairments).

Dimensionality and Input Speed Gaze-tracking and body-tracking approaches try to provide the user with a direct selection method. Therefore, is control is achieved, the user can control the pointer and through it achieve direct keyboard selection (using an on-screen keyboard) and event control directly other applications. On the other hand, there are some relative approaches that have a decreased input dimensionality and therefore lower speed (i.e., EOG joystick, Ultrasound Head Controller,...).

Eye movement input is faster that any other input media as before the user operates any mechanical device, he usually looks at his destination target (Jacob, 1993). However the doubt lingers if it should be used to directly select or as an auxilliary interface serving as an indicator.

Accuracy, Robustness and Repeatability One of the most common application of a computer interaction assistive device is the direct substitution of the mouse. Considering tracking approaches, several projects try to use the movement as a pointer direct controller (Evans et al., 2000). Moreover, the concept can be enlarged to wheelchair navigation.

Although gaze-tracking devices require an initial calibration and initially the system may be accurate, after a while the calibration starts to drift (Majaranta and Räihä, 2002).

Vision based approaches, although facing constant evolution, are still error prone considering position, orientation and illumination shifts while electromechanical approaches have a low signal to noise ratio, are sensitive to myographic and surrounding interferences.

Ease of use Although the tracking systems have evolved a lot and can be argued to be robust, there is some debate whether it makes sense to overload a perceptual organ by a motor task. On the other hand, gaze-tracking systems are very easy to operate as no training or particular ambientation is required (Evans et al., 2000).

On the other hand, the eye, the jerky way it moves and the fact that it rarely sits still present gaze-tracking approaches as inadequate to direct human computer manipulation (Jacob, 1993) . Moving the eye is almost an unconscious act and the user must change is attention focus to intentional use an eye-tracker as a mouse ("Midas Touch" problem). When using a mouse pointer we can look at several points without creating an action and the behaviour is not possible in a gaze-tracking setup. Also, eye-movements are always on, and unlike mechanical devices, it is not possible to turn on/off the device (unless a switch is added). This problem is reduced when considering face-tracking as the user may be looking at the results but if the head is steady no further commands are issued.

Aesthetics, Hygene and Acceptance Reflectance and appearance based tracking approaches have no issues regarding hygiene, aesthetics or user/social acceptance. In fact, eye and face tracking devices do not require any special setup and there is no discomfort considering the user. On the other hand, the fixtures inherent to an electrooculographic approach can be very annoying, creating high mental and physical awareness, although actual discomfort is low (Shaviv, 2002). However, latest user interfaces using EOG (headphone-alike) try to overcome this issue improving the user experience. Nevertheless, a complex setup is still required with awkward electrodes location and a rather unaesthetic scenario.

Mobility Adequacy The research around image processing is still evolving and none of the presented methods is really usable in a mobile scenario. Actually, light variations, voluntary and involuntary movements and the dependence on a signficantly large target screen are still obstacles to be surpassed. EOG approaches and eye-tracking glasses solve some of the above mentioned issues although the latter are still prone to light variations and miss-calibration errors.

As well, one of the major issues when considering mobility is the surrounding environment. Hence, considering scenarios where attention is required eye-based approaches are inadequate as the required eye control is incompatible with the need to observe the environment.

Maturity, Availability and Cost Electrooculography has significant advantages regarding other eye tracking methods as the equipment is cheap and can be used with glasses or contact lenses, unlike some reflection methods (Shaviv, 2002). However, looking at the actual panorama the maturity and availability of EOG interfaces is quite low. On the other hand, appearance-based tracking devices are cheap and available. The reflectance-based approaches (both Infrared and Ultrasound) are available for along time but they are still expensive.

5 Myographic Interfaces

Electromyography (EMG) is defined as the study of the muscular function through the analysis of the generated electric signals during muscular contractions. The potential difference obtained in the fibres can be registered in the surface of the human body through surface electrodes due to the biological tissues conducting properties (De Luca, 1997; Correia et al., 1992).

The recurrent and increasing electromyography study in medicine related areas led to a great scientific investment to improve the myographic signal acquisition and analysis process. These advances culminate with the possibility to use portable electromyographic devices that communicate via wireless with a processing system. Portability makes it possible for any individual the transport and use of a EMG device with great social acceptance (Costanza et al., 2004). EMG devices portability and reduced size easily conducted to its use in HCI with work carried through in the area of Accessibility, Robotics (Eriksson et al., 1998), Mobile Computation (Costanza et al., 2004; Costanza et al., 2005), among others. For example, Wheeler et al. (Wheeler and Jorgensen, 2003) presented Neuroelectric Joysticks and Keyboards, recognizing up to 9 wrist and hand motions (keypad) with a forearm band (Figure 24).

Considering assistive technologies several EMG-based systems have been developed aiming at computer keyboard and cursor control, wheelchair guidance, environment control among others like prosthesis control(Eriksson et al., 1998; AO and AB, 2001; Soares et al., 2003) or function electrical stimulation grasping systems (Saxena et al., 1995). We survey the most relevant approaches considering the target population and the goals of this research.

Computer Control

In 1997, Tarng et al.(Tarng et al., 1997) presented a myographic signal controlled human-computer interface considering quadriplegic users with C4 or below levels of injury. In this system, five electrodes are bilaterally placed on and between the

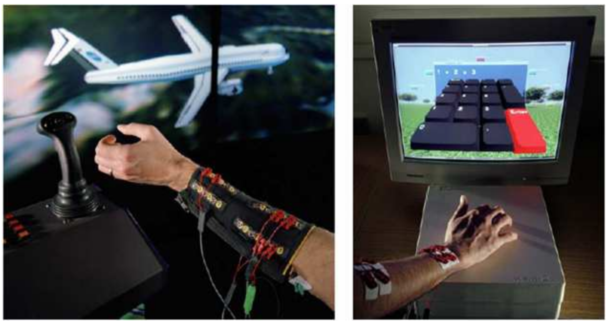


Figure 24: EMG Arm Joystick

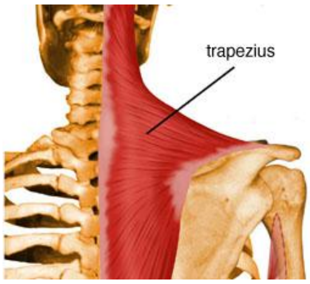


Figure 25: Trapezius muscle

upper trapezius (Figure 25) and sternocleidomastoid (Figure 26): for each pair of two electrodes, one is located over the sternocleidomastoid and the other over the upper trapezius; the ground electrode is located near the right earlobe. The subject is free to select five motions of head and shoulders and their recognition ratio is around 90%. With this system the user is able to control the mouse pointer (four directions and double-click) although the feature space and several parameters need to be adjusted before having a good classification ratio. The great advantage is for the the user to be able to select the motions to map with the actions. This was still preliminary work but a good motivation for several following EMG mouse pointer control interfaces.

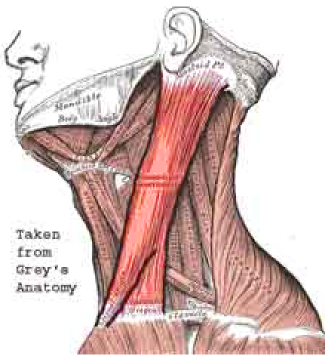


Figure 26: Sternocleidomastoid muscle

Park et al. (Park et al., 1999) suggested a single-switch EMG-based communication for disabled users whith severe motor and speech impairments. The users operate this system by chewing with the Masseter muscle achieving communication using morse-code through dots and lines, according to the contraction (chew) duration. The major limitation pointed out by the authors is the speed of the system, as disabled users sometimes are not able to chew and pause fast.

Aiming higher, Jeong et al. (Jeong et al., 2005) presented an EMG-based mouse control method for tetraplegic to operate computers by clenching teeth. The clenching actions were chosen due to the easiness in acquiring relevant signal patterns and due to teeth clenching subtleness, considering exposition to others. The signal is acquired on the *temporalis* muscle (Figure 27) attaching electrodes to an headband (Figure 28) or a cap. The system requires a training stage where a Fuzzy Min-Max

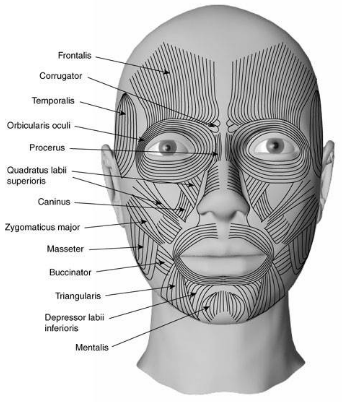


Figure 27: Face muscles

Neural Network is feeded with the Difference Absolute Mean Value at each channel. Two channels are recorded and four states are trained and further recognized with a 95% accuracy: rest, left-teeth clenching, right teeth-clenching and all-teeth clenching.

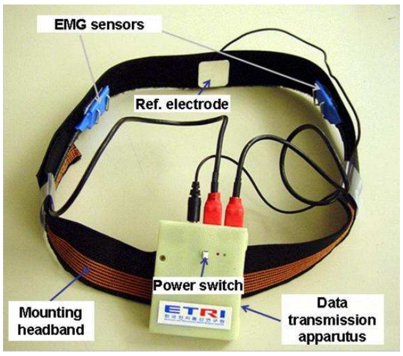


Figure 28: Jeong System Head Band

This system makes possible for users to control mouse with this restricted set of clenching actions by using left-teeth (2) and right-teeth clenching to adjust direction and using all-teeth clenching for moving the cursor in the selected direction and stoping (3,4). Selecting a target (i.e. clicking an icon) can be realized through double left-teeth clenching (Figure 29).

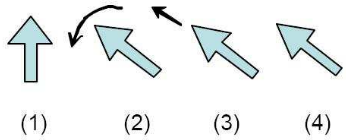


Figure 29: Jeong System Cursor Control Schema

The system can be used without disrupting the surrounding environment and without a large number of wires and electrodes.

HaMCos (Felzer and Freisleben, 2002a; Felzer and Nordmann, 2005; Felzer et al., 2005) system follows the same principles as the previous presented work focusing on EMG signals to control the mouse pointer. The system presented by the authors, although simpler and not so robust, is capable of detecting muscle contractions at any voluntarily contracted muscle group. Hence, HaMCos uses only one electrode and one muscle activation to issue commands, aiming at severe injured patients where other muscles could be out of control reach. The mouse pointer control relies on sequently wandering through the several possible states (left, right, up, down) and subsequently returning to STOP state. The user selects an action by contracting the monitored muscle when the system is at the desired state. Although more inefficient than other EMG approaches, it requires only one muscle group control aiming at a wider scope of disabilities and therefore users.

Felzer and Freisleben, HaMCos authors, developed a similar system but instead of using electromyography they used electroencephalography and instead of trying to decode the brain waves, they tried to capture movement-related bursts in the EEG signal (Felzer and Freisleben, 2002c). If EMG has greater amplitudes and signal to noise ratio than brain waves, why not just use it instead? - The authors rely on this rhetoric question.

Huang et al. (Huang et al., 2006) present an EMG human-computer interface but focusing only on facial muscles (Figure 27): the facial mouse. Four electrodes are placed on face voluntarily contracted muscles and 7 mouse functions (left; up, right, down, single right click, single left click and double left cick) are recognized. To detect the muscle activations this work adopts continuous wavelet transformation with a onset recognition rate greater than 80%. Each facial muscle activity maps a specific direction and the other actions are triggered with monitorized muscles activity combinations.

The presented systems focus on above-lesion electrodes placement and consider SCI injured individuals with high tetraplegia. Nevertheless, in other situations (i.e. incomplete injuries with some high member control), other muscles can be monitorized and therefore augment one's capabilities (Figure 30). There are several systems using EMG to control applications with any voluntarily contracted muscle (Guerreiro and Jorge, 2006; Rosenberg, 1998; Kim et al., 2004).

Wheelchair Guidance

Torsten Felzer and Bernd Freisleben developed the HaMCos project, already reviewed in this document. The HaWCoS (Felzer and Freisleben, 2002b) project relies on the same principles as HaMCoS, but this time applied to wheelchair guidance. With a single monitored muscle, the user can toogle between a set of events (left, halt, straight and halt) and therefore control an electrically powered wheelchair. The system is presented, through user evaluations, as imposing an overhead of less than 50% when compared with a traditional joystick.

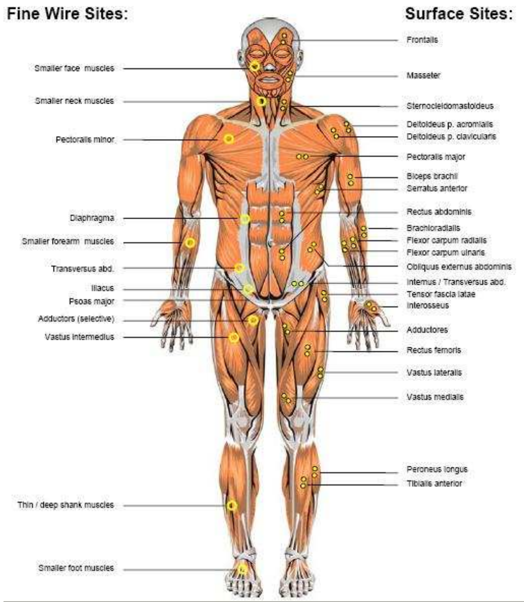


Figure 30: Electrodes Frontal Placement Possible Positions

Han et al. (Han et al., 2003) also developed an EMG-based human-machine interface for wheelchair control focusing on spinal cord injured individuals, particularly with C4 lesions. Upon user tests the Sternocleidomastoid muscle was chosen as the monitored muscle and actions are triggered by moving right shoulder up (right movement), left shoulder up (left movement) or both shoulders up (forward). Two modes were tested: in mode 1 the wheelchair goes forward while the user keeps the both shoulders up; in mode 2, "both shoulders up" action acts like a toggle which makes the wheelchair go forward or stop. Users preferred the toggle mode as it is less tiring

Moon et al. (Moon et al., 2004) present and interface for the above-elbow amputee or the lower extremities paralysis by C4 ou C5 spinal cord injury. Although they present several interaction prototypes including cursor control, their main concern is wheelchair guidance (Moon et al., 2005). The interaction basically consists of four commands also generated by three different shoulder elevation motions (left, right, both shoulders). EMG signals are collected in the Levator Scapulae muscles (Figure 31, processed and onset detection is tested with predetermined double threshold values. The authors show, through user evaluation that electromyographic wheelchair guidance is feasible for wheelchair control. However the system still lacks robustness due to predetermined double thresholds not suitable for different individuals and different usage conditions.

Environmental Control

Through computer control other devices can be controlled and therefore offer disabled users another scopes of interaction. Chen et al. (Chen et al., 2002) developed an EMG-controlled telephone interface for people with disabilities by using row-column scanning and an EMG-based trigger pulse. The users can trigger a selection with a neck contraction. Although the system is very simple it is also adaptable for almost any spinal cord injured individual restricted only for those who aren't able to contract their neck muscles (above C3 lesions).

Song et al. (Song et al., 2005) presented a system based on EMG signals to control the *Intelligent Sweet Home* which was developed to aid the living of the elderly and the disabled. It makes possible for users to control home-installed electronic devices using myographic signals with six wrist motions. In contrast to other projects depicted in this document this system aims at users with wider range of control as they must be able to control their wrist consistently. Although powerful considering the scope of interaction and devices controlled this system restringes the target population.

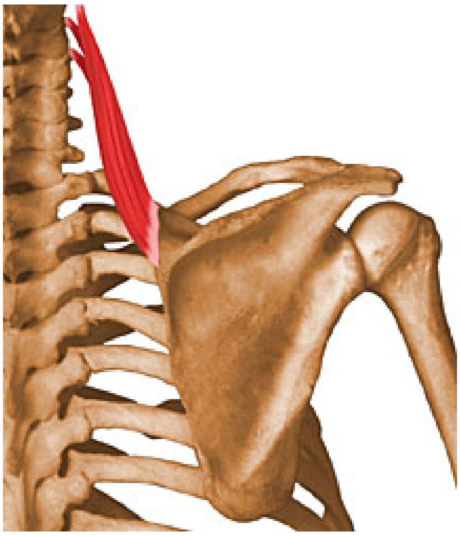


Figure 31: Levator Scapulae

Discussion on Electromyography

Although EMG-based systems are not comercially available to the common user, we can verify its mature use in several medicine related areas. The major drawback on electromyographic interaction is the complex setup that can hardly be called wearable. On the other hand, using surface electromyography it is possible to detect muscle onset and therefore associate events with pre-determined contractions or movements. Regarding the evaluation criteria:

Potential users range The number of voluntarily contracted muscles is large creating several acquistion scenarios, including cases where the impairments are enormous. The electrodes are placed accordingly to the lesion: the neck, jaw and temporal areas are presented as good choices. Therefore, there are several input sources that can be explored allowing higher degrees of control when several muscles are available but also to explore just one single muscle in the most severe cases, when no other input sources are available.

Dimensionality and Input Speed Considering myographic interaction, the dimensionality depends on the voluntarily contracted muscles set. Therefore, if one can control several muscle groups, we can argue that EMG has high dimensionality. On the other hand, considering the most severe impairments, the dimnesionality is also severly reduced. Moreover, although we have control on several muscle groups it would be difficult to interact with a keyboard with a EMG direct selection interface. EMG-based interfaces generally rely on a small set (from 1 to 4) monitored muscles.

Accuracy, Robustness and Repeatability An EMG-based solution is independent from ambient noise or surrounding movement in contrast to electroencephalography and voice based approaches. Also, when compared to other physiological signals, myographic signal presents the best signal-to-noise ratio and higher amplitudes, which eases its processing and makes it a good candidate to voluntary device control. The main problem in EMG-based interfaces is related with involuntary movements. This is even a greater problem when considering spasticity, a common collateral issue within the target population.

Ease of use Generally, on the user side, EMG-based applications are easy to use. Also, although some approaches rely on pattern recognition algorithms and therefore face a training phase, most of the surveyed approaches are based on simple signal processing techniques. On the other hand, and one of the reasons for its unavailability in the market, EMG interfaces require some attention on the electrodes montage. This problem is a current research issue (Jeong et al., 2005).

Aesthetics, Hygene and Acceptance The eletrodes placement and the wires are a big inconvenient that can make the users unconfortable. User and social acceptance issues also arise as considering some muscles it is difficult to hide the montage apparatus.

Mobility Adequacy The independence from a display creates the possibility to use EMG interfaces in a mobility scenario. Moreover, the signal characteristics are also adaptable and robust to a mobile scheme.

Maturity, Availability and Cost Electromyographic devices are on the market for several years. In the last few years, with component miniaturization and wireless technologies evolution, we have also witnessed the comercialization of portable wireless EMG devices. Although the cost is not huge it is still far from reach to the normal user and we can see it used in hospitals and physiatric clinics.

Figure 32: Brain-Computer Interface

6 Brain-Computer Interfaces

A Brain-Computer Interface (Figure 32) provides a direct interface between the brain and a computer.

A brain-computer interface is a communication system that does not depend on the brain's normal output pathways of peripherl nerves and muscles (Wolpaw, 2000).

A BCI consists on monitoring, through a brain-imaging technology, brain activity and detecting characteristic brain patterns associated with a certain action therefore achieving communication with the outside world. This technology creates a new interaction channel independent from muscle contractions suitable for severly disabled people who cannot use other assistive technologies that somehow rely on a certain physical ability. Particularly, for locked-in patients, the brain can be the only available communication channel. In these cases, the patients are completely paralyzed and unable to speak, but cognitively intact and alert. This condition can be caused by amyotrophic lateral sclerosis (ALS), brain stem stroke or high level spinal cord injure.

There are several techniques that can monitor brain activity: Magnetoencephalography (MEG), Magnetic Resonance Imaging (fMRI), Single Photon Emission Computer Tomography (SPECT), Positron Emission Tomography (PET) and Electroencephalography (EEG). However, EEG is the only practical brain imaging technology for the following reasons: inexpensive, ease of acquisition, high temporal resolution, real-time implementation and direct correlation of functional brain activity with EEG recordings (Wolpaw et al., 2002; Smith, 2004).

Electroencephalography (EEG) is a method used in measuring the electrical activity of the brain. This activity is generated by billions of nerve cells, called neurons. Each neuron is connected to thousands of other neurons and their combined electrical activity can be measured with scalp EEG. Although the temporal resolution of EEG is very good (beter than milisecond), the spatial resolution is poor.

Dependent and Independent BCI

A BCI is an alternative communication system in which messages or commands do not pass through the normal output pathways. Considering EEG-based BCIs, these messages are encoded in EEG activity. Although communication is realized through a different channel, in a dependent-BCI the normal output pathways activity is required to generate the brain activity reflected in the EEG. As an example, "one dependent BCI presents the user with a matrix of letters that flash one at a time, and the user selects a specific letter by looking directly at it so that the visual evoked potential (VEP) (Vidal, 1973) recorded from the scalp over visual cortex when that letter flashes is much larger that the VEPs when other leters flash (Sutter, 1992)".

On the other hand, an independent-BCI does not rely on the brain's normal output pathways. *For example, one independent-BCI presents the user with a matrix of letters that flash one at a time, and the user selects a specific letter by producing a P300 evoked potential when that letter flashes* (Wolpaw et al., 2002). In this case the EEG activity is generated by the user's intent and not by the precise orientation of the eyes.

Independent BCIs are of great interest due to their total separation from the normal output channels being studied as a communication and control alternative for locked-in patients.

BCI Types

There are several groups worldwide researching brain-computer interfaces separated in different categories, according to the type of EEG properties used. We will survey the most relevant approaches: Visual Evolked Potentials (VEP) are dependent BCIs because they depend on the gaze direction; those who use Slow Cortical Potentials, P300 Evoked Potentials, mu and beta rythms are believed to be independent BCIs.

Visual Evoked Potentials. Jacques Vidal developed the first dependent BCI (Vidal, 1973) which consisted on determining eye gaze direction using VEP recorded from the scalp over visual cortex. The system was able to determine the direction the user wanted to move the cursor. The Brain Response Interface (Sutter, 1992) also used VEPs recorded from the scalp over visual cortex to accomplish word processing tasks. The user selects a letter from a 8*8 matrix (64 symbols) by looking at the symbol he wants to select. Subgroups of these 64 symbols undergo an equiluminant red/green alternation or a fine red/green check pattern alternation 40/70 times/sec. Each symbol is included in several subgroups, and the entire set of subgroups is presented several times. Each subgroup's VEP amplitude about 100 ms after the stimulus is computed and compared to a template already established for the user determining the symbol that the user is looking at. Users were able to achieve a

10-12 words/min ratio. VEP-based BCI systems have the same function as gaze-tracking systems as they determine gaze direction.

Slow Cortical Potentials (SCP). SCPs are slow non-movement potential changes generated by the user which appear among the lowest frequency features of the scalp recorded EEG (Fatourechi et al., 2007; Wolpaw et al., 2002). These alterations can last from 300 ms to up to 10 seconds and several studies showed that it is possible to learn SCP control. The Thought Translation Device (TTD) is a BCI system where the user can control the movement of an object on a computer screen through its SCPs manipulation (Birbaumer et al., 1999). Birbaumer and his team also used the TTD with a language support program to provide word processing capabilites and Internet access to disabled users, allowing selection of up to 3 letters/min (Birbaumer et al., 2000). The program enables the user to select a letter by a series of two-choices selection (from chunks to letters) and it's usable 24h/day as it provides a stand-by mode controlled by the user (through a combination of positive and negative SCPs).

P300 Evoked Potentials. P300 is a positive peak in the EEG at about 300 ms after a particularly significant auditory, visual or somatosensory stimuli which appears among frequent or routine stimlumi (Fatourechi et al., 2007; Farwell and Donchin, 1988). Donchin et al. (Farwell and Donchin, 1988; Donchin et al., 2000) presented a word processing application of a P300-based BCI: the user is presented with a 6*6 matrix contaning the alphabet letters. One row or column is randomly intensified every 125 ms, flashing all rows and colums, in an overall of 12 flashes. The system is based in an oddball paradigm as the user has to focus in a relevant cell, which constitues 16,7% of the intensifications (2 in 12), eliciting the P300 (Donchin et al., 2000; Wolpaw et al., 2002; Lehtonen, 2002). Bayliss and Ballard (Bayliss and Ballard, 2000) focused on a virtual environment navigation using the P300, instructing the users to drive in a virtual town and stop at red lights. This scenario although limited (response to different semaphore lights) allows the subjects to decide in an online dynamical environment instead of the traditional visual continuous tasks with rare stimulus occurences. Results suggested that single-switch P300 could be used to control devices such as TVs, radios among others. Piccione et al. (Piccione et al., 2006; Hoffmann et al., 2007) showed that the P300 could also be used to control a 2D cursor using a 4 choice paradigm (four arrows), each of the arrows flashing every 2.5s in a random order in the peripheral area of the screen. Although the disabled could operate the cursor with the developed system, the average communication speed is very low. Other P300 based BCIs have been developed to improve disabled users' communication capabilities (Sellers et al., 2006; Hoffmann et al., 2007) with similar approaches.

Mu and Beta rhythms. The human brain waves present different rhytmic activity according to the level of consciousness and are affected by different actions and thoughts. The EEG is divided into several frequency ranges which are named after greek letters (delta, theta, alpha, beta, gamma) although other brain rythms have been proposed in the EEG literature. One of them is the mu rythm which frequency is around 10 Hz and although similar in frequency and amplitude to the alpha rythm, Mu rythm is topologically and physiologically different. Mu stands for motor and this rythm is strongly related to motor cortex function and somatosensory cortex (Lehtonen, 2002). Some beta rythms are harmonics of mu rythms but some are separable and thus are different EEG features. Several Mu and beta rythm-based BCIs have been developed since the mid-1980s as these rythms association with cortical areas most directly connected to movement or preparation of movement are believed to be good signal features for EEG-based communication (Wolpaw et al., 2002).

With the Wadsworth BCI (Wolpaw and McFarland, 2004; Wolpaw et al., 2002), disabled users learn to control mu or beta rythm amplitudes and therefore control the cursor in one or two dimensions. In the early stages users tend do employ motor imagery to control the cursor but over the training sessions, the imagery relevance decreases and users move the cursor like they perform conventional motor actions. Users achieved information transfer rates up to 20-25 bits/min (Wolpaw and McFarland, 2004). Their studies also included answer to yes/no questions where a 95% accuracy was achieved.

The Graz-BCI is focused on distinguishing between the imagination of different simple motor actions, such as left or right foot or hand movement (Pfurtscheller et al., 2000). The system also enables a tetraplegic patient to control a mechanical hand-orthosis (Figure 33) using two types of motor imagery (Pfurtscheller et al., 2003).

Regardless of the approach, a current BCI-system can offer locked-in patients the ability to communicate at transfer rates of up to 25 bits/min easing several applications' control (Answer simple questions, Word Processing, Control neuroprosthesis (Muller-Putz et al., 2005), Control the environment (Aloise et al., 2006; Cincotti et al., 2006, ASPICE Project), Navigate within virtual and augmented reality environments (Navarro, 2004; Pfurtscheller et al., 2006), Control and Electric Wheelchair (Tanaka et al., 2005)

Discussion on Brain-Computer Interfaces

Brain-computer interface technology is the less mature among those surveyed in this document. Although research in this area has been evolving in the last few years, is is generally agreed that a long path is still to come. Nevertheless, it is an insteresting technology as the brain can be the only output path to communication. Therefore, the main advantage on brain-compute interfaces is its suitability to a wide range of users.

Potential users range Although interfaces based on eye-gaze or EMG are more efficient than any of the BCIs available for severly disabled persons, a BCI can be the only communication tool for people suffering from locked-in syndrome, when no other output channel is available (Lehtonen, 2002). *BCIs do offer a potentially valuable new option for restoring communication and control to*

Figure 33: Neuroprosthesis Control

people with disabilities (Wolpaw, 2007).

Dimensionality and Input Speed The communication is still very slow (around 25 bits/min). Also, the selection set must be very limited to achieve good recognition results. Considering the actual research panorama, it is hard to evaluate the future of Brain-Computer Interfaces as the opinions are very different.

Accuracy, Robustness and Repeatability On the other hand, BCI development is still in its earliest stages and current systems are still very limited, embrionary and error prone. Although recognition rates reported are high, BCI-based systems have not gone out of the laboratory and therefore these results are still higly constrained and obtained within restricted conditions, free of distractions and higly supervised. Also, the achieved results are still very variable within sessions and days even with prolonged practice. The EEG signal is highly sensitive to noise with a low signal to noise ratio, has low amplitudes and it is extremely fragile to artifact contamination (EMG and EOG artifacts due to blinks or facial movement as well as other external interferences).

Ease of use Operating a BCI system still demands high attention and cognitive loads which makes it difficult to use in noisy and distractive environments restricting the interaction scenarios. Also, the montage still requires some specialist attention and can hardly be used by a normal user within his daily scenario.

Aesthetics, Hygene and Acceptance The need to use a somehow awkward helmet and a set of wires around the head may be an obstacle to some users due to social acceptance issues.

Mobility Adequacy Nowadays, we can already find BCI solutions for mobile devices. However, the BCI use hardly copes with a mobile scenario as the interferences to the system and the distractions to the user are enormous. The authors aren't aware of any BCI system successfully used in a mobile scenario.

Maturity, Availability and Cost One can find EEG systems comercially available and simple Brain-Computer Interfaces but their costs are still prohibitive to the common user. However, some rehabilitation centers and hospitals are already working with this technology.

Figure 34: Sip and Puff switch

7 Breath-Based Interfaces

One of the most common assistive technologies for communication and control is the Sip'N Puff switch 34, a binary action pneumatic device capable of sensing airflow direction through an easy accessible piece of tubing similar to a drinking straw (Surdilovic and Zhang, 2006). This kind of switches require little or no movement and offer an easy and unobtrusive way to operate a device. On the other hand, these types of devices cannot sense airflow intensity, restricting the interaction to a yes/no paradigm (Kitto, 1993; Kitto and Harris, 1994b). This type of switch is needed for individuals who do not have the motor skills to reliably produce a mechanical, repetitive movement.

Searching for a higher degree of control, Kitto et al. (Kitto and Harris, 1994a), developed a synergy between a sip and puff switch and a chin joystick, creating the Sip and Puff Mouse. The important feature of this design is that the extended joystick is controlled by chin motion of the individual whose chin cup is custom molded (vacuum molded). A tube from the sip and puff circuit rests in the mouth of the individual to replace the mechanical button. Sip represents the left or right mouse bottom. Puff then represents the other mouse button. Since the circuit has individual adjustments for sip and puff, the device suits a wide range of individuals. Double clicking is easily accomplished by double sipping and double puffing. The device can be attached to the computer table or to a table attached to the wheelchair of the user.

The *"Breath-Joystick"* (Grigori and Tatiana, 2000) is a device highly sensitive to the human respiration flow. The setup consists on six thermo transducers located in front of the user's mouth, selecting necessary components of directed air stream. While four transducers emulate the X and Y coordinates, the other two emulate left and right buttons. The thermo transducers work at a temperature above 40ºC, which removes undesirable water vapor influence. Although using a mouse's micro-controller and serial port, the device operates like a joystick, with a *deadband* where no movement occurs. When the air stream is outside of this deadband (above defined threshold) the mouse cursor is moved with defined "Steps" and "Frequency", and continues to move until air flow is below threshold. Therefore, when a user desires to move the cursor in a certain direction, he must send air flow between respective thermo-transducers and must keep the air pressure until the cursor reaches the desired location.

The presented system is an alternative to regular sip-puff switches and augments the scope of interaction as several input channels are present (four directions and two buttons). However, the authors don't present enough results to declare it as an advantage to others. User's still need to have an awkward mechanism in front of their mouse and it is not clear how user's can distinguish the different actions. Is is also not clear if severe spinal cord injured individuals would be able to use the system, as lip movement and breath functions can be highly damaged.

Michel and Rancour (Michel, 2004) propose the use of thermal imaging to detect breath patterns. This idea main advantage is that the person doesn't need *to be precisely aimed at the infrared sensor because the thermal pattern is "visible" over a wide range of angles*. The system provides a less cumbersome technology for user's who are currently served by sip-puff systems. Also, this system has a wider scope of potential users since the users need less movement control. It is still a work in progress and there are no guarantees that the heat plumes can tell us as much as the authors desire.

Recently, (Patel and Abowd, 2007) presented an approach (BLUI) where the user blows at the laptop or computer screen to control interactive applications. In order to locate the blowing, the authors rely solely on a microphone, similar to those embebbed in standard laptops. It is important to notice that the system relies on the wind created and not on the sound, so the interaction can be made without disrupting the environment. The authors present a set of actions which the user is able to operate like selection, scrolling and dragging. The system was evaluated with three users, each one peforming a set of 25-50 blows, after a training phase.

	3 x 3	4 x 4	5 x 5	6 x 6
Laptop	100%	96 %	80%	62%
Desktop	100%	92 %	82%	66%

Table 2: BLUI Evaluation (% of correctly identified regions)

Shorrock et al. (Shorrock et al., 2004) present another technique to communicate by breath alone. *A belt-mounted breath-mouse, delivering a signal related to lung volume, enables a user to communicate by breath alone.* Basically, an optical mouse is attached to a piece of wood, to which a belt is also attached. When the user breathes his/her diaphragm moves, making the optical mouse to slide on the piece of wood and generating pointer movement. The system is specially designed to work with Dasher (Ward et al., 2000), in one-Dimensional mode. Evaluations show that Breath-Dasher outperforms Sip-Puff Morse interfaces. Although interesting for text-entry and persons with total breath capabilities, the system is limited to other applications.

Figure 35: Breath Mouse

Discussion on Breath Interfaces

The sip and puff switch is the most known breath-based approach, it is commercially available and used by a large number of disabled individuals. However, this device restrictions are huge and other breath-based interfaces were studied to overcome those limitations. Overall, breath-based interfaces are advantageous as they are available to a wide users scope but still have a slow input speed and questionable ease of use.

Potential users range The ability to control diaphragmatic function, which is required to breath, is compromised when the impairment is high (above C3). Therefore, not all the users have fine breath control, requiring ventilation. Overall, the presented breath-based interfaces are unavailable to that particular user scope. On the other hand, below C4 impaired users are prone to have fine breath control and are therefore possible users, whether consdiering sip-puff switches, whether considering approaches where higher head control is required (i.e., BLUI where the user needs to face a target when blowing).

Dimensionality and Input Speed The sip and puff switches are the breath-based most used interfaces. There are several problems with sip and puff switches that limit their use. One regards their low bandwith which reduces the interaction speed as well as the interaction scenarios. Other breath-based approaches enlarge the selection set and increase the dimensionality and therefore the input speed. However, the interaction speed is still limited and these approaches are only aimed at mouse pointer emulation. Nevertheless, recent research (BLUI) presents motivating results that are prone to improve breath-based interaction as the selection set is already appreaciable.

Accuracy, Robustness and Repeatability The sip and puff switches are normally accurate. Other presented Breath-based interfaces, although aiming to solve some of the sip and puff switch problems are still embrionary and no taxative results have been presented. Also, it is not clear how these systems will behave in public where several flows can be present. Therefore, their robustness and repeatability is questionable.

Ease of use For those who have good breath control, sip and puff switches are not difficult to operate and require little adaptation phases. Other breath-based approaches, although increasing the selection set, are based on the same functions and appear to be easy to use. However, some of the approaches require a classification stage, increasing the usage setup time and installation dialogues. Another downside on breath-based approaches is the inhability to control the device and talk at the same time (Vanderheiden and Smith, 1989).

Aesthetics, Hygene and Acceptance Considering sip and puff switches, one can argue that it is rather inconvenient to use and presents some hygiene and ergonomics issues therefore limiting user and social acceptance. The other breath-based interfaces overcome this issue and face no aesthetics or hygiene problem as no contact is required between the mouth and the device.

Mobility Adequacy In opposite to the other evaluation characteristics, the contact requirement offers sip and puff switches the required stability and robustness to face a mobile scenario. Actually, there are several electronic wheelchair guided by sip and puff switches. On the other hand, non-contact breath interfaces use the air flow from the user's mouth to control the device but we have no results showing that these interfaces will perform well within an outdoor scenario where several air flows may be present (wind, other people,...)

Maturity, Availability and Cost The most relevant breath-based interface is the Sip and Puff switch due to its simplicity and high scope of interaction considering the target population. It is comercially available and can be used to answer simple yes/no questions but also to communicate, for example, using morse code (Shorrock et al., 2004).

8 Overall Discussion

Along this document, we surveyed each technology group, presenting relevant projects and therefore being able to analyze it taking several evaluation critertia into account. The technology characteristics and technology use within a certain scenario (that define a selection set and method) give uses the neccessary data to assess technological capabilities and limitations.

In this chapter, we are now able to compare the surveyed technologies folllowing a criteria-based approach for the evaluation points previously defined. The overall comparison is presented in Figure 36. Each of the columns is discussed below.

Categories	Variations	Potential users	Dimensionality	Accuracy	Ease of use	Aesthetics / Hygiene	Mobility Adequacy	Cost
Switches, Sticks and Pointers								
	Upper-Limb	★	★	★★★	★★★	★★★	★★★	★★★
	Mouth and Tongue	★★★	★★	★★	★★	★	★★★	★
	Other head-based	★★	★	★★★	★★★	★★★	★★★	★★★
Vocal								
	Speech	★★★	★★★	★★	★★★	★★	★	★★★
	Accoustic	★★★	★★★	★★	★★	★★	★	★
	Aural Flow	★★★	★★	★	★★	★★	★★	★
	Tooth touch	★★★	★★	★	★★	★★★	★★★	★
Tracking								
	Electrooculography	★★★	★★	★★	★★	★	★★	★
	Head Optical Pointers	★★	★★★	★★	★★	★★	★	★★
	Eye-Tracking	★★★	★★★	★★	★★	★★★	★	★
	Other Reflectance Tracking	★★	★★★	★★	★★	★★	★	★★
	Feature Tracking	★★	★★★	★	★★	★★★	★	★★★
Electromyography		★★★	★★	★★	★★	★★	★★★	★
Electroencephalography		★★★	★	★	★	★	★	★
Breath								
	Contact (i.e., Sip-puff)	★★	★	★★	★★	★	★★★	★★★
	Non-Contact (i.e., Heat Flow)	★★	★	★	★★	★★★	★★	★

Figure 36: Overall Evaluation

Potential users range (Figure 37)

Categories	Variations	Potential users
Switches, Sticks and Pointers		
	Upper-Limb	★
	Mouth and Tongue	★★★
	Other head-based	★★
Vocal		
	Speech	★★★
	Accoustic	★★★
	Aural Flow	★★★
	Tooth touch	★★★
Tracking		
	Electrooculography	★★★
	Head Optical Pointers	★★
	Eye-Tracking	★★★
	Other Reflectance Tracking	★★
	Feature Tracking	★★
Electromyography		★★★
Electroencephalography		★★★
Breath		
	Contact (i.e., Sip-puff)	★★
	Non-Contact (i.e., Heat Flow)	★★

Figure 37: Potential Users Evaluation

As seen along the document, there are approaches focused at a specific and limited user group while others have a wider scope of possible users. It is therefore relevant to analyze the availability of a certain assistive technology to the various target populations. The potential users of each assistive technology group is presented in Figure 37.

Although the most severly injuries can eventually impair speech and mouth-related functions, we consider all face-based approaches as extensive. Therefore, all the approaches that are able to measure any kind of input from the eye (EOG, Eye-Tracking), mouth (tongue and vocal) or face muscles are included in this group. Considering spinal cord injuries, these technologies are prone to be available to the most severe injured patients (even above C3). Breath-approaches are not included in this group as ventilator need is probable.

In a second technology group, we include all the approaches available to the users that are able to move their head and detain breath and inteligible speech capabilities. This group includes C3-C5 impaired users.

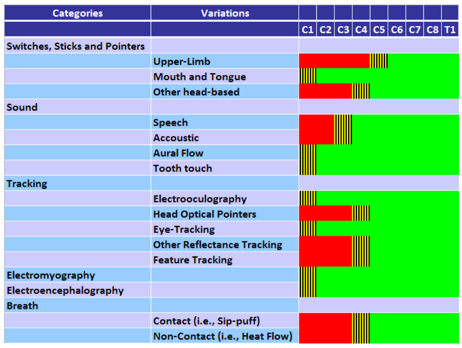


Figure 38: Matching map

Below C5 impaired users detain some upper-limb control and are therefore able to control switches, joysticks or other similar approaches (Arm EMG).

Figure 38 presents the matching map between the assistive technologies surveyed and the different motor capabilities and corresponding motor map. Although the assistive categories cover a wide group of techologies we pointed out for each of them the most probable acquired capability (i.e., to use a arm switch one shall have at least some bicep function (C4)). There are some situations where users with lesions above the pointed vertebrae can control a device within the group but that control is very limited. Also, individuals with a incomplete injury may present motor abilities that offer the possibility to control above lesion pointed devices but generally the classification can be folllowed.

Dimensionality and Input Speed (Figure 39)

Dimensionality is highly related with the possible interfacing schemes achieved with each technology, considering several scenarios, including those where the selection set is large. The high dimensionality approaches are those who are able to offer direct selection even when the selection set is considerable. The approaches included in this group are voice-based (speech and accoustic) as the vocabulary can be defined accordingly to the selection set and eye-based approaches that, through the adequate interface, can achieve selection set completness (i.e., direct selection on an on-screen

Categories	Variations	Dimensionality
Switches, Sticks and Pointers		
	Upper-Limb	★
	Mouth and Tongue	★★
	Other head-based	★
Vocal		
	Speech	★★★
	Accoustic	★★★
	Aural Flow	★★
	Tooth touch	★★
Tracking		
	Electrooculography	★★
	Head Optical Pointers	★★★
	Eye-Tracking	★★★
	Other Reflectance Tracking	★★★
	Feature Tracking	★★★
Electromyography		★★
Electroencephalography		★
Breath		
	Contact (i.e., Sip-puff)	★
	Non-Contact (i.e., Heat Flow)	★

Figure 39: Dimensionality and Input Speed Evaluation

keyboard).

While the other approaches are not able to offer direct selection for large selection sets, there are ones that suit that selection method with limited (but considerable) input set cardinality (EMG, EOG, Aural Flow, Tooth touch, Tongue and Mouth switches) or can be used within an enconding scheme.

Other approaches highly restrict the cardinality of the input set and are normally used with an auxilliary scanning interface. User performance is highly damaged.

Accuracy, Robustness and Repeatability (Figure 40)

Categories	Variations	Accuracy
Switches, Sticks and Pointers		
	Upper-Limb	★★★
	Mouth and Tongue	★★
	Other head-based	★★★
Vocal		
	Speech	★★
	Accoustic	★★
	Aural Flow	★
	Tooth touch	★
Tracking		
	Electrooculography	★★
	Head Optical Pointers	★★
	Eye-Tracking	★★
	Other Reflectance Tracking	★★
	Feature Tracking	★
Electromyography		★★
Electroencephalography		★
Breath		
	Contact (i.e., Sip-puff)	★★
	Non-Contact (i.e., Heat Flow)	★

Figure 40: Accuracy, Robustness and Repetability Evaluation

The most accurate approaches are those that are independent from any recognition algorithm and are independent from the surrounding environment (Touch switches). On the other hand, the less accurate are those still embrionary considering recognition and/or are higly sensitive to the environment (Aural Flow, Feature Tracking, Heat Flow, EEG). In the middle, we considered all the approaches that suffer from one of those problems. Speech research can be argued to have surpassed the recognition issue but this is not true lin noisy environments while all the computer vision approaches are still vulnerable to artifacts and interferences from the surrounding environment. This is also true for electrophysiological approaches.

Ease of use (Figure 41)

Categories	Variations	Ease of use
Switches, Sticks and Pointers		
	Upper-Limb	★★★
	Mouth and Tongue	★★
	Other head-based	★★★
Vocal		
	Speech	★★★
	Accoustic	★★
	Aural Flow	★★
	Tooth touch	★★
Tracking		
	Electrooculography	★★
	Head Optical Pointers	★★
	Eye-Tracking	★★
	Other Reflectance Tracking	★★
	Feature Tracking	★★
Electromyography		★★
Electroencephalography		★
Breath		
	Contact (i.e., Sip-puff)	★★
	Non-Contact (i.e., Heat Flow)	★★

Figure 41: Ease of use Evaluation

The hardest technology to use is the brain-computer interface due to the setup apparatus and the large training required. If a comercial product is delivered neccessary training must be offered both to the users and caregivers. Althoguh with a reduced complexity almost all the approaches require some training, habituation or some montage apparatus that can difficult its use. Speech and touch switches are the ones that offer no obstacles to the user, not even in the first approach.

Aesthetics, Hygene and Acceptance (Figure 42)

Categories	Variations	Aesthetics / Hygiene
Switches, Sticks and Pointers		
	Upper-Limb	★★★
	Mouth and Tongue	★
	Other head-based	★★★
Vocal		
	Speech	★★
	Accoustic	★★
	Aural Flow	★★
	Tooth touch	★★★
Tracking		
	Electrooculography	★
	Head Optical Pointers	★★
	Eye-Tracking	★★★
	Other Reflectance Tracking	★★
	Feature Tracking	★★★
Electromyography		★★
Electroencephalography		★
Breath		
	Contact (i.e., Sip-puff)	★
	Non-Contact (i.e., Heat Flow)	★★★

Figure 42: Aesthetics, Hygene and Acceptance Evaluation

All the approaches that obey visible fixtures in the user's body are prone to be rejected due to social acceptance issues. Also, some approaches imply some discomfort and can even harm the user. Vocal approaches that can somehow disrupt the surrounding environment and can break the user's privacy while interacting with the system in public are also prone not to be accepted..

On the other hand, there are approaches that need no extra hardware on the user's body and cn be used subtely (i.e., Touch switches, EMG, Tooth touch, Tracking and Non-Contact breath).

Mobility Adequacy (Figure 43)

Categories	Variations	Mobility Adequacy
Switches, Sticks and Pointers		
	Upper-Limb	★★★
	Mouth and Tongue	★★★
	Other head-based	★★★
Vocal		
	Speech	★
	Accoustic	★
	Aural Flow	★★
	Tooth touch	★★★
Tracking		
	Electrooculography	★★
	Head Optical Pointers	★
	Eye-Tracking	★
	Other Reflectance Tracking	★
	Feature Tracking	★
Electromyography		★★★
Electroencephalography		★
Breath		
	Contact (i.e., Sip-puff)	★★★
	Non-Contact (i.e., Heat Flow)	★★

Figure 43: Mobility Adequacy Evaluation

A mobile approach must offer independence from a computer screen and must not be disruptive to other user tasks. While within a mobile scenario (i.e., driving a wheelchair in a public space) the user must be aware of his surroundings and should be able to simultaneously perform a task in his mobile device. Also, mobile approaches must be immune to movement, noise and electromechanical interferences.

Maturity, Availability and Cost (Figure 44)

Categories	Variations	Cost
Switches, Sticks and Pointers		
	Upper-Limb	★★★
	Mouth and Tongue	★
	Other head-based	★★★
Vocal		
	Speech	★★★
	Accoustic	★
	Aural Flow	★
	Tooth touch	★
Tracking		
	Electrooculography	★
	Head Optical Pointers	★★
	Eye-Tracking	★
	Other Reflectance Tracking	★★
	Feature Tracking	★★★
Electromyography		★
Electroencephalography		★
Breath		
	Contact (i.e., Sip-puff)	★★★
	Non-Contact (i.e., Heat Flow)	★

Figure 44: Maturity, Availability and Cost Evaluation

Most of the surveyed technologies have a representant product in the market stating that they are somehow mature. Figure 45 presents some products and prices placed

Categories	Variations	Example Product	Price Range (in Euros)
Switches, Sticks and Pointers			
	Upper-Limb	**Gumball Switch from Enabling Devices**	*10 - 100*
	Mouth and Tongue	**Tongue Touck Keypad from New Abilities**	*5.000 - 10.000*
	Other head-based	**TetraMouse Chin Joystick**	*100 - 250*
Vocal			
	Speech	**Windows Vista Speech Recognizer**	*Free (*)*
	Accoustic		*N/A*
	Aural Flow	**e-macc from Think-a-Move**	*3.500 - 5.000*
	Tooth touch		*N/A*
Tracking			
	Electrooculography	**bioplux from Plux**	*1.500 - 7.500*
	Head Optical Pointers	**Lomak from Opdo**	*750 - 1.000*
	Eye-Tracking	**MyTobii P10**	*5.000 - 10.000*
	Other Reflectance Tracking	**Tracker Pro from Madentec**	*500 - 1.000*
	Feature Tracking	**Camera Mouse**	*100 - 250*
Electromyography		**bioplux from Plux**	*1.500 - 7.500*
Electroencephalography			*N/A*
Breath			
	Contact (i.e., Sip-puff)	**Sip and Puff switch from Origin Instruments**	*100 - 250*
	Non-Contact (i.e., Heat Flow)		*N/A*

Figure 45: Product availability and price

within a reasonable range. While other products with different prices can be found, the presented products are comercially successful and can be stated as representative. In the figure we can observe a large difference between prices that should be taken into account when selecting an assistive technology.

9 Conclusions

In this survey, we presented several projects among different technologies that share the same goal: offer the motorly disabled greater control and communication capabilities, greater autonomy. We can identify projects aiming at different user groups, at different scenarios and with different control approaches. It is important to notice that for a particular situation, one approach is better than all the rest but also that each of the presented approaches is the most suitable to a determined case. The presented comparisons provide the neccessary tool for the assessment of a certain technology and its suitability to a specific user.

However, it is also important to focus that although the presented projects show great evolution and offer the disabled with command, control and communication mechanisms, a long path is still ahead. While the latest research is still mainly focused on technical issues, the user and his daily requirements are still to be fullfilled. Thus, it is still hard to select an assistive system that maximizes the user's capabilities fullfilling his requirements, and achieve this through several scenarios and environments. The assistive interaction is still higly restrictive! And completness on every aspect is the next goal to achieve....

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