Curtin University

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Design and development of Infrared activated tongue computer interaction system

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university except where due acknowledgment has been made.

Acknowledgements

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Abbreviations

AT	Assistive Technology
BCI	Brain Computer Interface(s)
EEG	Electroencephalography
EMGTCI	Electromyography Tongue Computer Interface
GKPTCI	Glassokinetic Potential Tongue Computer Interface
HMI	Human Machine Interface/Interaction
IR	Infrared
ITAB	Infrared Tongue Activated Beacon
IRTSHCIS	Infrared Tongue Supported Human Computer Interaction System
IRTCIS	Infrared activated Tongue Computer Interaction System
LDA	Linear Discriminant Analysis
PDCA	Peripheral Device Control Apparatus
SCI	Spinal Cord Injuries
SVM	Support Vector Machine
TCI	Tongue Computer Interface
TDS	Tongue Drive System

Abstract

Around seventy-five million people in the world live with some form of physical disability caused by either neuromuscular disorder, Spinal Cord injuries or degenerative disease. These people need continuous support to perform everyday tasks. They need assistance to engage with the world around. Therefore, research toward improving the quality of such people's life is very important. Considerable research is underway to develop human machine interfaces for helping people with physical disabilities communicate with the world around.

This thesis reports a novel approach to translate tongue voluntary motion data into user-specific parametric tongue position models which are then used to train a classifier. The classifier is then tested to localise tongue movements into cursor movement on screen. It can be used by rehabilitation centres and researchers to develop tongue assistive technology. The system, designed and developed to let disabled people use tongue for interacting with computers, is called InfraRed (IR) Activated Tongue-Computer Interaction System (IRTCIS). It employs an infrared proximity sensor array to capture the tongue movement.

The work builds upon the past research at Curtin University on the use of the tongue for interacting with machines and operating assistive devices. The thesis goal was to gain insight into factors that limit tongue-computer interaction systems' application in real life and develop a better IRTCIS. This investigation is a step forward toward designing and developing a new approach for tongue computer interaction. The main objective of the presented research was to design and implement a less invasive system using infrared proximity sensors to sense tongue movement and localise them into cursor movements on screen.

The IRTCIS detects the user's tongue movements using an array of IR proximity sensors placed in front of the face with the help of a 3D printed mask. It translates IR proximity sensors data into cursor movements on the computer screen using a machine learning algorithm.

The IRTCIS is a minimally invasive device requiring no physical attachment to the tongue or to the mouth oral cavity. The system was able to generate user-specific parametric tongue

position models that could be used to train a classifier. The research has demonstrated possibilities of classifying the tongue movements and using them for moving a cursor on screen. However further enhancements are required to use the IRTCIS as an assistive technology.

This work covered the six important dimensions of designing and implementing the IRTCIS:

1. Investigated the design and implementation of existing tongue operated assistive systems.
2. Developed and built the IRTCIS prototype to verify the concept of detecting voluntary tongue movements with the aid of IR proximity sensor array.
3. Modelled parametric tongue positions.
4. Trained and validates a classifier.
5. Implemented the prototype system in real-time for adoption of this assistive device.

The IRTCIS and the parametric tongue position models generated by the system present a novel approach for communicating with computers using infrared proximity sensors. It is a less invasive method of communication which allows interaction with computer without any electrical installations inside mouth. The models generated by the system were used to train a Linear Discriminant Analysis (LDA) classifier which achieved the overall accuracy of 95.4% to predict correct tongue position. During the experiments, the IRTCIS in real-time was able to translate tongue movements into cursor movement with the throughput of 0.45 pixels per second. With further development, the IRTCIS can be used by rehabilitation and research centres to let patients generate alarms or type short messages when needed.

Major Contributions

- ✓ Designed and Developed the IRTCIS prototype
- ✓ Tested IRTCIS prototype
- ✓ Developed parametric tongue position models
- ✓ Trained a Classifier
- ✓ Validated the classifier results
- ✓ Tested classifier in real-time

Chapter 1

Introduction

1.1 Motivation

One in six people in Australia live with some form of disability. Over three-quarters (76.8%) of these people reported living with physical disabilities [1]. Physical disability can be caused by Spinal Cord Injuries, neuromuscular disorder, multiple sclerosis, or stroke. People living with these disease may suffer from loss of muscle function for one or more muscles. It can occur in localised or generalised manner or it may even follow some pattern. Depending on the severity of the problem, the individual can suffer impairment in motor or sensory function of all four limbs and torso.

A study initiated by the Christopher and Dana Reeve Foundation found that 5,596,000 people in the US, almost 1 in 50, are living with paralysis. 16% of these individuals (about one million) have said that they are completely unable to move and cannot live without continuous help[2]. According to the German Federal Statistical Office there are 4.7 million people who were diagnosed with severe physical disability in 2013 in Germany alone [3]. Globally, 75 million people around the world live with physical disability.

These statistics may be an evolutionary average, but the number of people affected by physical disability represents a significant part of the world population. People with disabilities are more likely to experience adverse socioeconomic outcomes such as less education, poorer health outcomes, lower levels of employment, and higher poverty rates[4]. These people depend heavily on special care services and their families for everyday routine tasks that can be a burden mentally, physically and financially. Table 1 below shows the average yearly medical and care cost for person suffered from SCI as per a study done by Christopher and Dana Reeve Foundation [5].

Severity of Injury	**First Year**	**Each Subsequent Year**
High Tetraplegia (C1-C4) ASIS ABC	$1,064,716	$184,891
Low Tetraplegia (C5-C8)	$769,351	$113,423
Paraplegia	$518,904	$68,739
Incomplete motor function (any level)	$347,484	$42,206

Table 1: Yearly cost for Spinal Cord Injuries based on severity [5]

The support and services needed by people living with physical disabilities can include, life skills development, specialist accommodation and home modifications, personal care and domestic assistance, support to participate in community activities, etc. Therefore, research toward improving the quality of life of this underserved population can potentially have a large societal impact.

An Assistive device can reduce the need for continuous help, thus reduce the health care costs and increase the productive, less dependent hours of people with disabilities.

1.2 Assistive technology (AT)

1.2.1 Definitions

Assistive technology is “any item, piece of equipment or product system whether acquired commercially off the shelf, modified, or customized that is used to increase, maintain or improve functional capabilities of individuals with disabilities”, defined by the Technology-Related Assistance for individuals with Disabilities Act of 1998 [6].

The early development of modern assistive technology can be marked by examples like Braille system developed by Louis Braille for blind people to read and write. Hearing aids that can help people with hearing impairments by amplifying the sounds. Lightweight foldable wheelchair for people with walking disability. Ever since the assistive technology industry have grown rapidly with the innovation in new materials and technologies. Efforts have been made to improve the quality of life of people with disabilities.

For our application, assistive technology can be defined as a system that can enable people with motor disabilities, use their remaining abilities, to obtain control over devices in their environment such as using controlling a powered wheel chair, operating an alarm system, accessing a computer.

Motor disabilities can be referred to diseases or injuries which causes significant and persistent limitations to a person’s body movement, examples are Spinal Cord Injuries (SCIs), and strokes.

With the evolution of technology, once an impaired person is enabled to use computers, the possibilities for him to perform routine tasks without continuous assistance are endless. *Figure 1* below shows the possible applications of assistive technology which can help people with physical disabilities control their environment.

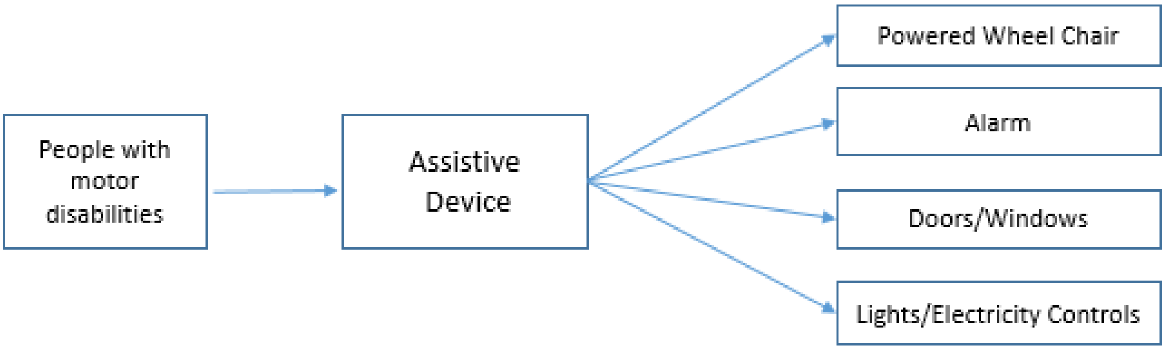


Figure 1: Applications of assistive device

1.2.2 Limitations of existing ATs

Considerable amount of efforts have been underway to develop an AT that can help people interact with computer such as invasive and non-invasive Brain Computer Interfaces (BCIs), eye tracker, speech control, head tracking. Apart from usability problems such as issuing commands which are not intended by the user, ease of use, muscle fatigues are other problems with these ATs.

Based on the literature, Electroencephalography (EEG) based Brain Computer Interfaces (BCIs) available have limited bandwidth and not suitable for unpredicted situation therefore cannot be used outside the testing environment. Few invasive BCIs are faster, give better control and have less noise issues but they are very costly and intrusive. Eye gaze tracking systems interfere with regular visual tasks. Currently eye tracking systems are unable to be used to navigate electric wheelchairs, as it is not possible for patients to scan ahead to view the surroundings and steer the wheelchair at the same time [38]. Head movement systems such as require certain level of movement which may not be present with high level injury people [39], they also cause fatigue and neck and shoulder pain. The interfaces using voice commands are very effective for computer access in quiet environments but they are neither reliable nor safe in noisy and outdoor environment.

Tongue controlled devices seem to present less noise issues and muscle fatigue therefore more suitable for people suffering with high level Spinal Cord Injuries and other motor neuron disease that can cause quadriplegia. Few examples of Tongue-based ATs are Inductive Tongue Control System [40], Tongue Rudder [21], and Tongue Drive System (TDS) [18]. Majority of these systems use complex and intrusive mechanisms that require mounting of sensors inside mouth cavity like magnetic sensors in TDS, Hall Effect proximity sensors in Peripheral Device Control Apparatus (PDCA), magnetic coils, electrodes etc. Inside mouth installation in above Tongue controlled devices may hinder with speech and eating and also impose hygiene issues. The complexity of the above mentioned systems is still keeping them away from the real world applications.

1.3 Reasons to explore tongue assistive technology

Literature supports that tongue ATs show promising results with less limitations compared to other human machine interfaces because of the following inherent capabilities of tongue muscle.

- The tongue is known for generally escaping severe damage in SCIs and most neuromuscular disorders as it is connected to brain via hypoglossal nerve.
- Tongue motion is intuitive and does not require thinking or concentration like BCIs.
- Tongue and mouth occupy an amount of sensory and motor cortex in the human brain that rivals that of the fingers and the hand. Hence, they are inherently capable of sophisticated motor control and manipulation tasks with many degrees of freedom. [7]
- Tongue muscles have low rate of perceived exertion, therefore it does not cause fatigue for users like eye and head controllers and can be used continuously for several hours. [8]
- The tongue is noninvasively accessible, and its motion is not influenced by the position of the rest of the body.

The author aims to simplify the tongue sensing mechanism so that a low-cost, minimally invasive system can be designed. This research explores the possibility of developing an external feature space for tongue position localisation.

1.4 Research Objective and Scope

The aim of this research project is to design and implement a minimally invasive, low-cost and easy to use Infrared based tongue computer interaction system.

The main contributions of presented research are parametric tongue models that are used to localise tongue position and Infrared proximity sensor array design that created external feature space for tongue position localisation. That array was used to develop parametric tongue model for each defined tongue position. Machine learning techniques are then applied on the parametric models to train a classifier.

This project designed and fabricated a system that can detect user's voluntary tongue motion using array of IR proximity sensors. For each tongue position, an array of voltages was generated which is referred as feature array for that specific tongue position. Then the parametric tongue models were generated for six tongue positions. The device does not require tongue to touch or press against anything or installing any component inside mouth.

The system was successfully able to generate unique parametric tongue model for specific tongue positions and the generated tongue models were able to train a classifier with 92% accuracy of predicting correct output.

1.4.1 Research Scope

Following tasks define the scope of this research:

- Investigate existing Tongue Assistive devices
- External Feature space for tongue position localisation

  Design and fabricate IR proximity sensor based wearable system to localize tongue position
- Develop parametric tongue models.
- Train classifier

  Use the Parametric models generated by this research to train a classifier.

  Test the Classifier
- Real time implementation of the presented system to achieve cursor control

Chapter 2

Background

2.1 Chapter Introduction

This chapter enlightens the reader about the target demography of this research. It states the medical reasons which can cause the physical disabilities in people. The chapter then gives a brief introduction to Human Machine Interface/Interaction (HMI) and discusses some of the Tongue Assistive Technology developed in this decade.

This research intent to develop a tongue computer interaction system that is easy to use and is external to the mouth. The research proposes that it can be used for rehabilitation services and also has the possibility to be employed as assistive system with further clinical investigations for people living with quadriplegia.

2.2 Application background

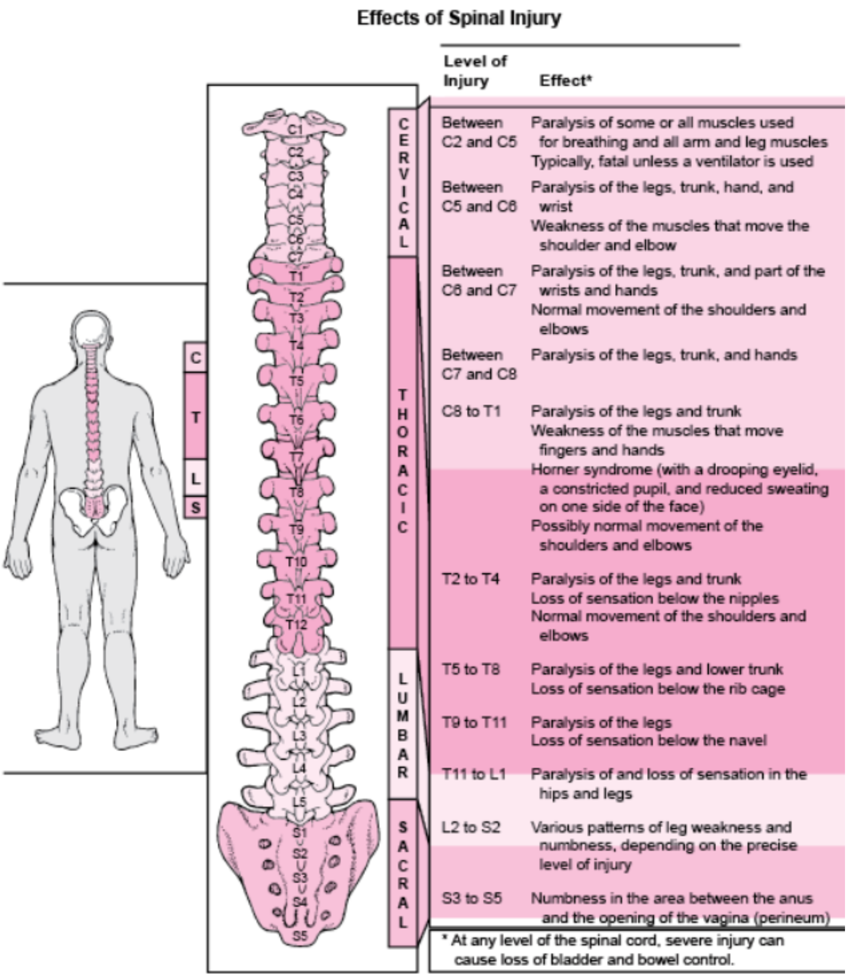
Our target demography is patients living with spinal cord injuries, paralysis, neuromuscular disorder or any such unfortunate incident which leave them with no or partial control over their leg and arm movements. The research can enable researchers and rehabilitation centres to develop tongue assistive device suitable for people living with physical disabilities caused by spinal cord injuries, degenerative diseases, and motor neuron disorders.

Next section will discuss the spinal cord anatomy and effects of spinal cord injuries, and other disorders that can lead to people losing control over their limbs and torso.

2.2.1 Spinal cord anatomy

The spinal cord is the main source of communication between the brain and the rest of the body. It starts from the base of the brain and extends downward to the pelvis. It comprise of cervical(C), thoracic (T), lumbar (L) and sacral(S) regions. Each of these regions consist of eight, twelve, five and five vertebra respectively.

Along the length of the spinal cord, 31 pairs of spinal nerves emerge through spaces between the vertebrae. Each spinal nerve runs from a specific vertebra in the spinal cord to a specific area of the body. Based on this fact, the skin’s surface has been divided into areas called dermatomes. A dermatome is an area of skin whose sensory nerves all come from a single spinal nerve root. Loss of sensation in a particular dermatome enables doctors to locate where the spinal cord is damaged[9]. The Figure 2 below shows the effects of spinal cord injury on the human body based on the location/level of the injury.



Effects of Spinal Injury

Level of Injury	Effect*
Between C2 and C5	Paralysis of some or all muscles used for breathing and all arm and leg muscles Typically, fatal unless a ventilator is used
Between C5 and C6	Paralysis of the legs, trunk, hand, and wrist Weakness of the muscles that move the shoulder and elbow
Between C6 and C7	Paralysis of the legs, trunk, and part of the wrists and hands Normal movement of the shoulders and elbows
Between C7 and C8	Paralysis of the legs, trunk, and hands
C8 to T1	Paralysis of the legs and trunk Weakness of the muscles that move fingers and hands Horner syndrome (with a drooping eyelid, a constricted pupil, and reduced sweating on one side of the face) Possibly normal movement of the shoulders and elbows
T2 to T4	Paralysis of the legs and trunk Loss of sensation below the nipples Normal movement of the shoulders and elbows
T5 to T8	Paralysis of the legs and lower trunk Loss of sensation below the rib cage
T9 to T11	Paralysis of the legs Loss of sensation below the navel
T11 to L1	Paralysis of and loss of sensation in the hips and legs
L2 to S2	Various patterns of leg weakness and numbness, depending on the precise level of injury
S3 to S5	Numbness in the area between the anus and the opening of the vagina (perineum)

* At any level of the spinal cord, severe injury can cause loss of bladder and bowel control.

Figure 2: Spinal cord structure and effects of spinal cord injuries [9]

2.2.2 Spinal cord disorders

In general spinal cord disorder causes muscle weakness, loss of sensation, paralysis. Doctors determine the damaged part of the spinal cord by identifying the specific location of symptoms (for example, which muscles are paralysed and which parts of the body lack sensation)[9]. Functions controlled by areas of the spinal cord below the damage may be completely or partially lost. Functions controlled by areas of the spinal cord above the damage are not affected.

For this project our main focus is on patients with cervical spinal cord injuries which have no or partial control over their arms, legs and trunk. Injuries at or below C8 cause paralysis of legs and trunk but the patient still preserve some level of finger and hand muscle flexion, at C7 patient may extend their elbows. Between C6 and C7 patient may be able to move their shoulders and elbow but have paralysis of legs trunk and parts of wrist and hands. Between C5 and C6 patient's elbow and shoulder muscle weakens. Between C3 and C5 patient's neck muscle control between. Between C1 and C3 patient may feel difficulty breathing and may depend on ventilator, paralysis of all arms and legs muscles.

This project may also be used by the patients suffering from degenerative diseases depending on the state of their disease. In the following paragraph two of the degenerative disease are discussed where patients may get benefit from tongue assistive device.

2.2.3 Multiple Sclerosis

Multiple Sclerosis causes degeneration of the nerves within the central nervous system. Over the time it effects multiple bodily functions such as, walking talking and writing, Figure 3 below shows its effects on body. Patients are left being wheelchair bound and have only a small amount of movement in their head neck and shoulders. Assistive tools which utilise head and neck movement can be used by the patients. As their condition worsens only control of eyes will remain. Between the two above mentioned cases, tongue assistive device can be an efficient mode of communication.

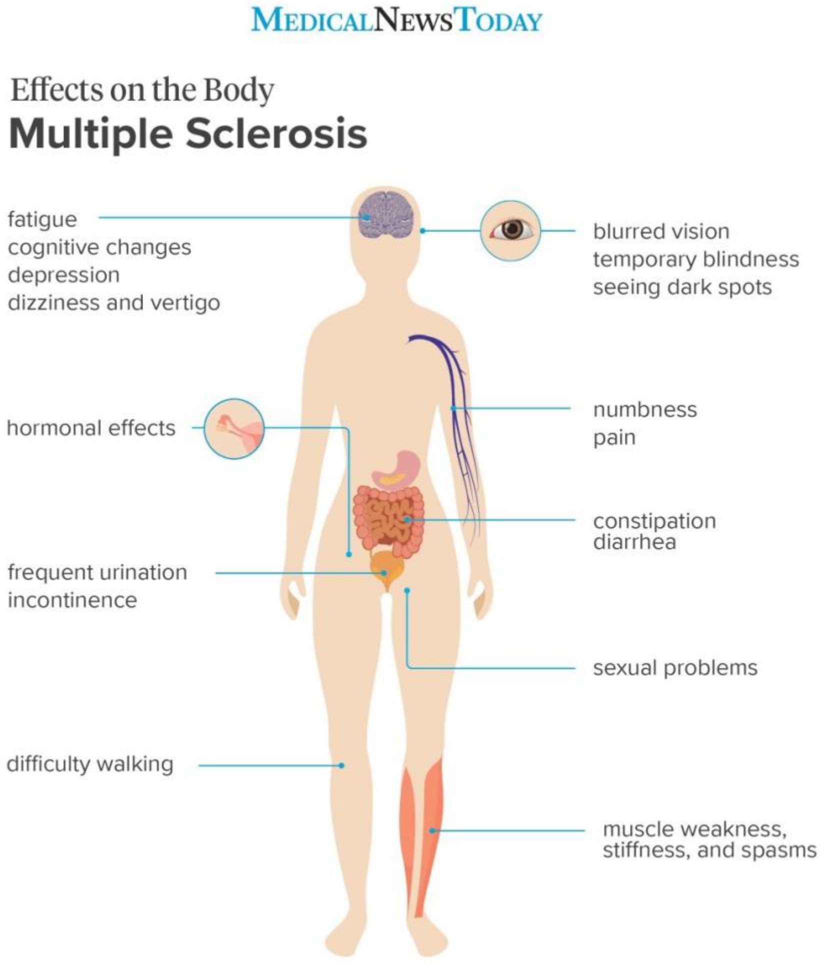


Figure 3: Effects of multiple sclerosis on body [10]

2.2.4 Motor neuron disease

The Motor Neurone Disease involve the degeneration of the nerve cells. Motor neurones are nerve cells that control the voluntary muscles of the trunk, limbs, speech, swallowing and breathing[11]. Weakness issues begins with the hands or feet and as the nerves become further damaged the patient's condition worsens leading to paralysis, loss of speech. The tongue can also get effected in these patients and it can only be used in the initial stages of the disease. The patient will be required to go under assessment and if the tongue muscle are not weak only then tongue assistive device will be beneficial for patients suffering motor neuron disease.

The above discussed literature proves that a large number of people who suffer from spinal cord injuries and degenerative diseases can lose partial or complete control over their body and they will need continuous help to perform everyday tasks. Assistive technology can reduce the level of care they require, hence health care costs will reduce and the independence of ill patients will improve. This leads to a happier outcome for the patient whilst also relieves the strain which carers may be under.

In next section we will discuss the existing research for human computer interfaces and reflect on the gap that can be filled by this research.

2.3 Human Computer Interface for Assistive technology

Human Computer Interaction typically employs the use of hand to convey user intentions to computer while it's performing well for healthy people our target population which is suffering from cervical spinal cord injury or neuromuscular disorder is clearly at a disadvantage. Several Human Computer Interfaces (HCIs) has been developed using the remaining capabilities of abovementioned demography which are eye gaze, speech, head movement, tongue movement and brain signals.

Despite the wide variety of HCIs developed, most of them still couldn't come out of the lab environment and academic grounds. Also the few which make it to commercial market have limitations and are complicated to use.

Electroencephalographic (EEG) based Brain Computer Interfaces (BCIs) available have limited bandwidth and not suitable for use outside the testing environment. Few invasive BCIs are faster, give better control and have less noise issues but they are very costly and intrusive. Eye gaze tracking systems interfere with regular visual tasks. Head movement systems require certain level of movement and can cause fatigue and neck and shoulder pain. The interfaces using voice commands are effective for computer access in quiet environments but they are not reliable in noisy environment. Available Tongue computer Interfaces (TCIs) show that the technique provide sufficient level of control to communicate with computer but most of these systems are highly invasive and are still under development after years of research.

In following section we will analyse the tongue anatomy and muscles strength that will show the significance of using tongue over other available modalities for our application demography.

2.4 Tongue as Input Modality

The tongue is connected to the brain via the hypoglossal nerve, which generally escapes severe damage in Spinal Cord Injuries (SCIs) and most neuromuscular disorders. As a result, patients with high-level SCIs still maintain tongue control capabilities. The map of the human motor cortex in *Figure 4* illustrates that the tongue and mouth occupy a significant amount of sensory and motor cortex in the brain that rivals that of the fingers and hands. Therefore, they are inherently capable of sophisticated motor control and manipulation tasks[12]. Consequently, this makes the tongue an ideal input for communication systems which would be used by immobile patients. The tongue muscle has a low rate of perceived exertion and does not fatigue easily[8].

To further investigate the capabilities of the tongue, this section will cover the complete anatomy of the tongue, focusing upon its key muscle groups which allow for movement.

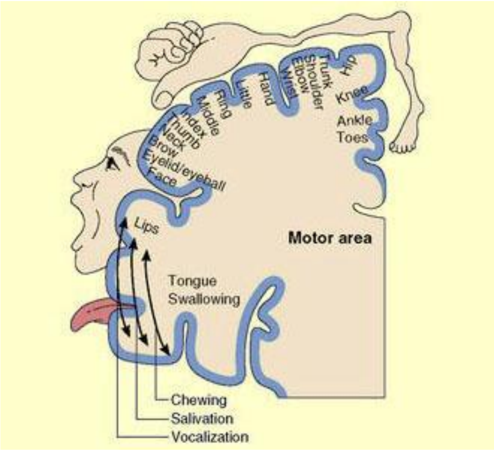


Figure 4: Human motor cortex map [12]

2.4.1 Tongue Anatomy

The tongue is a muscular organ in the mouth. It can perform a wide range of tasks that help the human body to operate efficiently. Its main functions include the sensation of taste, mastication (chewing), deglutition (swallowing), digestion, speech, and clearing the oral cavity. The tongue is also capable to act as a sensory organ which means it can transfer information to the brain regarding pressure, pain, heat, and taste. The reason behind its multi-tasking abilities is due to its muscular structure, the tongue is constructed of skeletal muscle fibres which allow the user to manipulate and control the position of the tongue with a high degree of precision[13].

2.4.2 Tongue Muscles

The tongue is an entirely muscular organ. It is separated medially into two halves by a connective septum. "A thin partition or membrane that divides two cavities or soft masses of tissue in an organism"[14]. The septum means that the tongue and its muscles are laterally symmetrical. *Figure 5* shows tongue muscles that can be divided into two distinct groups, Intrinsic and Extrinsic.

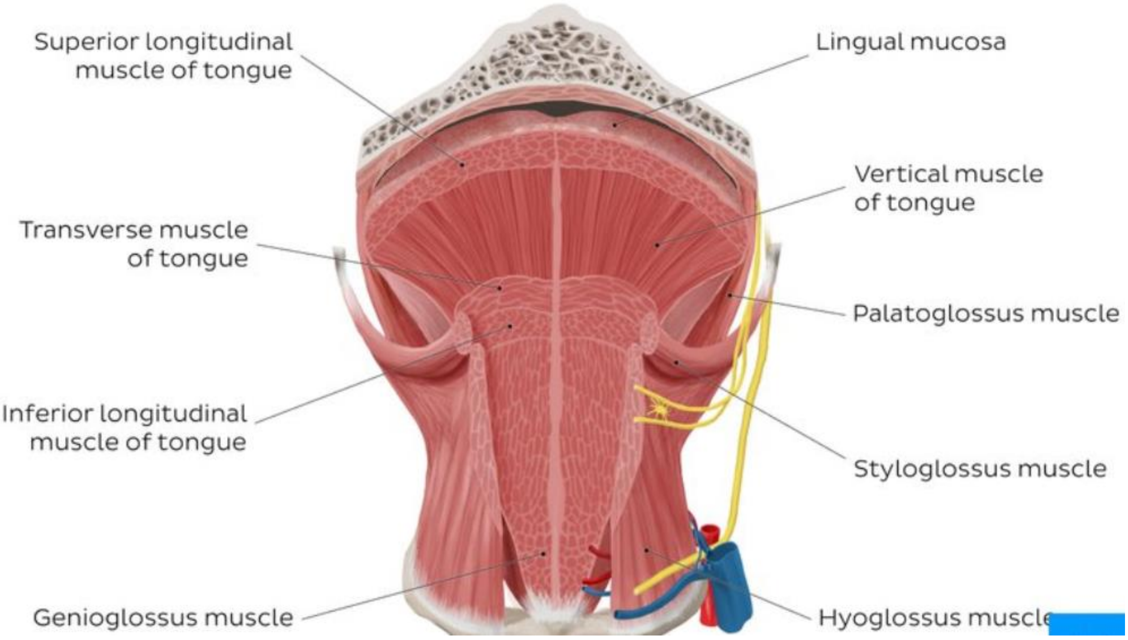


Figure 5: Tongue Muscles [15]

2.4.2.1 Intrinsic Muscles

Intrinsic muscles are placed within the tongue and make the core of it. Their main function is altering the shape of the tongue. They are superior longitudinal, inferior longitudinal, transverse, and vertical muscles. These muscles all work together to produce movements that are essential for mastication (chewing), speech, and deglutition (swallowing). These movements include elongating and retracting the tongue, elevating and lowering the apex of the tongue, and broadening and narrowing the surface of the tongue. Refer to Table 2 for action relevant to each muscle in the group.

Muscle	Key features
Superior longitudinal	Origin - submucosa of the posterior tongue, lingual septum Insertion - apex/anterolateral margins of tongue Action - retracts and broadens tongue, elevates apex of the tongue
Inferior longitudinal	Origin - the root of the tongue, body of the hyoid bone Insertion - the apex of the tongue Action - retracts and broadens tongue, lowers apex of the tongue
Transverse muscle	Origin - lingual septum Insertion - lateral margin of tongue Action - narrows and elongates tongue
Vertical muscle	Origin - the root of the tongue, the genioglossus muscle Insertion - lingual aponeurosis Action – Broadens and elongates tongue

Table 2: Intrinsic muscles and their key features [15]

2.4.2.2 Extrinsic Muscles

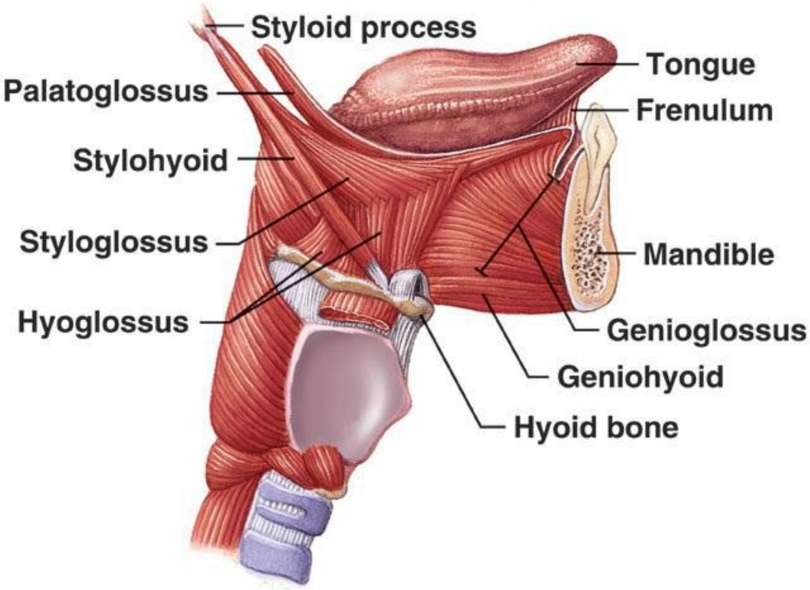


Figure 6: Extrinsic muscle group [15]

Extrinsic muscles as shown in *Figure 6* comprise the muscles that are outside the tongue but are functionally associated with it and help it perform its function. Their main function is altering the position of the tongue. They are genioglossus, hyoglossus, and styloglossus, and palatoglossus muscles. They produce those movements of the tongue which the intrinsic muscles can't, which are protrusion, retraction/retrusion, depression, and elevation of the tongue. They allow the organ to move in three distinct directions: up and down, side to side as well as protrusion and retraction. Refer to Table 3 for key feature of each muscle.

Muscle	Key features
Genioglossus	Origin - Superior mental spine of mandibleInsertion - the entire length of the dorsum of the tongue, lingual aponeurosis, body of the hyoid bone Action - depresses and protrudes tongue (bilateral contraction); deviates tongue contralaterally (unilateral contraction)
Hyoglossus	Origin - body and greater horn of hyoid bone Insertion - inferior/ventral parts of lateral tongue

	Action – depresses and retracts tongue
Styloglossus	Origin - anterolateral aspect of styloid process (of temporal bone), stylomandibular ligament Insertion - blends with inferior longitudinal muscle (longitudinal part); blends with hyoglossus muscle (oblique part) Action - retracts and elevates lateral aspects of tongue
Palatoglossus	Origin - palatine aponeurosis of the soft palate Insertion - lateral margins of tongue, blends with intrinsic muscles of the tongue Action - elevates root of the tongue, constricts isthmus of fauces

Table 3: Extrinsic muscles and their key features [15]

2.4.3 Tongue Movement

The human body is a complex machine, consisting not only of simple links and joints but highly meticulous muscle interactions which are difficult for biomedical engineers to mimic. For example, the human hand has 26 degrees of freedom alone[13].

Most input devices used today such as mouse and touchpad have only two degrees of freedom, they can move independently in both the x and y directions. Thus constraining the input mechanism to two degrees of freedom makes sense because most screens available today are also two dimensional. Therefore the aim is to design an input mechanism for the tongue which is being able to use its remarkable dexterity and map its signals back into a two-dimensional frame of movement, where it can be used to control a variety of devices such as telephones, wheelchair navigation systems and operating systems.

The studies on movements of the tongue are primarily focused on speech. When we speak, our tongue undergoes different movements that are very natural and completed so easily that we don't realise how the tongue is moving. In the rest position, the tongue is located on the palate tissue just behind the upper teeth. This is a relaxed position for the tongue and it returns to this position after use.

Tongue movements in speech are made along two primary degrees of freedom: the high-front to the low-back axis and the high-back to the low-front axis, based upon the existing knowledge from numerous studies[16]. Perrier concluded that "the degrees of freedom extracted for different languages from articulatory data are not speech specific, but are due to the anatomical and biomechanical properties of the tongue. Speech control would then use these degrees of freedom to determine and differentiate the articulations of the different sounds of a language"[16]. Therefore from this statement, it is possible to conclude that the use of the tongue is limited by its anatomical and biomechanical properties, speech has evolved to incorporate these limitations by using the tongue and its muscle groups as effectively as possible. By incorporating these movements into a conceptual design for a communication device, will achieve the most efficient method of transferring information from the tongue to the input system.

2.4.4 Tongue Muscle Strength and Endurance

Now knowing that tongue can be manipulated and hence is suitable for being used as an input medium, further literature presents the muscle strength and endurance capabilities of the tongue.

Muscular strength refers to the amount of force a muscle can produce with a single maximal effort.

Muscular endurance refers to the ability of a given muscle to exert force, consistently and repetitively, over a period.

Table 4 shows the tongue strength and endurance values produced by the study conducted by Ship and Crow in 1996[17].

Age Group	n	Tongue Strength (kPa)	Tongue Endurance (sec)
19-39	16	75.7±17.3	43.9±21.3
40-59	27	75.2±23.6	41.9±24.3

60-79	43	69.5±17.3	48.0±40.8
80-96	13	53.7±13.3	45.2±25.5

Table 4: Results produced by Tongue strength and endurance study [17]

The Iowa Oral Performance Instrument (IOPI, 12-14) was used to determine the tongue strength and endurance. Maximal pressure for the tongue was determined by recording three maximal force efforts, each of approximate one-second duration, with a one-minute rest period between trials. Endurance was measured by asking subjects to maintain 50% of their maximal pressure for as long as possible. The length of the endurance trial was measured in seconds[17].

From *Table 4* the mean minimum tongue strength value is 53.7 kPa, this value must be taken into consideration when designing the interaction device. Our aim is to design a communication device for immobile people, therefore the amount of effort required to use the device must be far less than the minimum pressure capable by a regular person.

In the context of tongue communication devices, the important fact to note is that the end user can be using the tongue continuously for longer hours and performing repeated tasks. Therefore, using only 50% of the maximum muscle strength can lead to pain and damage of muscles. Even though *Table 4* shows that the mean minimum tongue endurance at 50% of the maximum muscle strength is 41.9 seconds, this figure should be regarded as an absolute maximum for design considerations.

In the light of the tongue anatomy and its muscle strength study, it can be concluded that the tongue is a very strong muscle and its inherent capabilities make it useful as an input medium in the communication system. However, the tongue like any other muscle has some limits, according to studies to reduce the risk of repetitive strain injuries the tongue must be operating at less than 50% of its maximum strength capacity.

Therefore, It can be suggested that the interactive part of the tongue communication system should be able to operate with as minimal force as possible and facilitate the tongue movement in its natural movement axis; high front to the low back axis, and a high back to the low front axis.

2.5 Related Work

Many Tongue Computer Interface systems have been developed, availing the capabilities of tongue, to assist people with high level SCIs and neuromuscular disorders. As discussed in previous sections tongue is inherently capable of sophisticated motor control and manipulation tasks with many degrees of freedom[12].

Existing TCIs include; Tongue Drive System (TDS) [18], Inductive Tongue Computer Interface (ITCI), Infrared Tongue Activated Beacon (ITAB) [13], Infrared Tongue Supported Human Computer Interaction System (IRTSHCIS) [7], Intraoral Tongue Drive System (iTDS) [19], Tongue Computer Interface using Electromyography [20]. Majority of these systems uses electronics installed inside mouth cavity like magnetic sensors in TDS, piezoelectric sensors, pressure sensors, magnetic coils, electrodes etc. In the next section of this chapter, we will discuss following Tongue Computer Interaction Systems in detail;

- Tongue Drive System (TDS) [18,19]
- Intraoral Electromyography Tongue Computer Interface (EMGTCI) [20]
- Tongue rudder- Glassokinetic Potential based tongue machine interface (GKPTCI) [21]
- Infrared based wearable tongue controlled assistive device [23]
- Infrared Tongue Activated Beacon (ITAB) [17]
- Infrared tongue supported human computer interaction system (IRTSHCIS) [7]

2.5.1 Tongue Drive System (TDS)

There are two versions of TDS; External TDS (eTDS) and Intraoral Tongue Drive System (iTDS). TDS, shown in Figure 7, employs the phenomenon of Magnetic Resistance. A permanent magnet is attached to the tongue inside mouth to generate magnetic field. Magnetic sensors are used to detect the changes in magnetic field caused by movement of magnet which in turn makes detection of tongue movement possible. The sensor output is then transmitted to computer where they are processed, classified and turned into user-defined control commands. These commands are then communicated to the aimed devices in the environment.

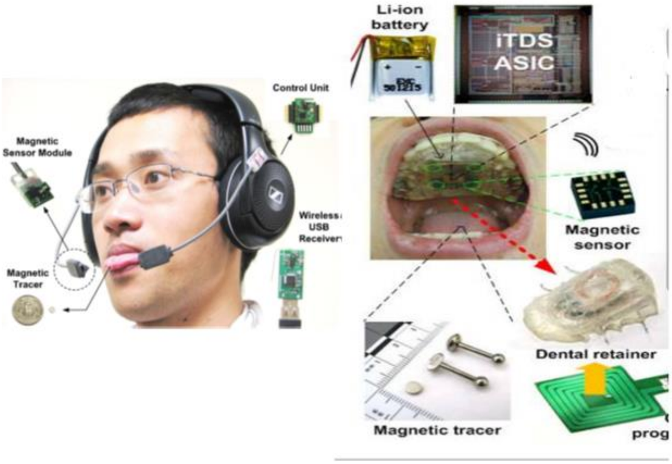


Figure 7: eTDS and iTDS [18, 19]

In eTDS the four 3-axial magneto-resistive sensors are mounted on goosenecks of headset which are symmetrical to the sagittal plane of body where as in iTDS sensors are mounted on the four corners of the PCB attached to the upper teeth inside mouth to detect the variation in magnetic field caused by tongue movement so the sensors face totally different working environments.

The eTDS uses simple 2.4 GHz frequency transmission whereas selecting the data transmission frequency for iTDS was based on its complex intraoral design. The carrier signal had to pass through human tissues and muscles which work as an attenuator. Therefore the frequency of 27MHz which shows the smallest attenuation was selected however it is also used as short distance radio so tends to have more external interference. To address these problems dual band transmitter is employed which switches between the frequencies (27MHZ, 423MHz) depending on external interferences. The design of intraoral miniature antenna is yet a challenge.

The eTDS component chips are mounted on wireless headset while iTDS electronics are on dental retainer. The eTDS faced the mechanical stability design issue while iTDS requires invasive procedure to mount the magnet and also a dentist required for fitting dental retainer which makes iTDS intrusive and costly.

2.5.2 Intraoral Electromyography Tongue Computer Interface (EMGTCI)

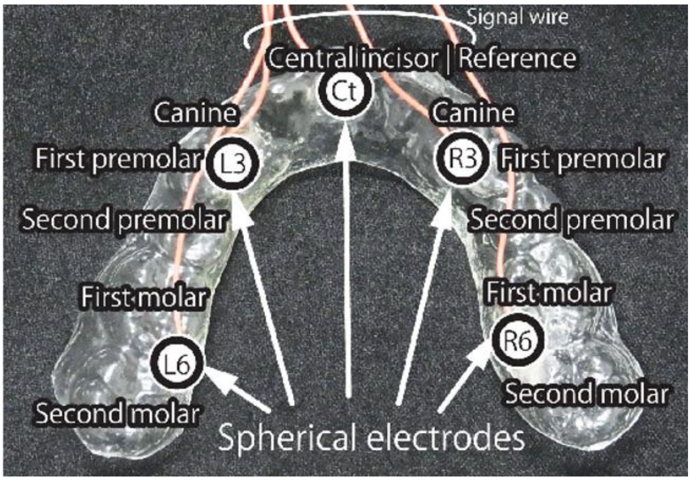
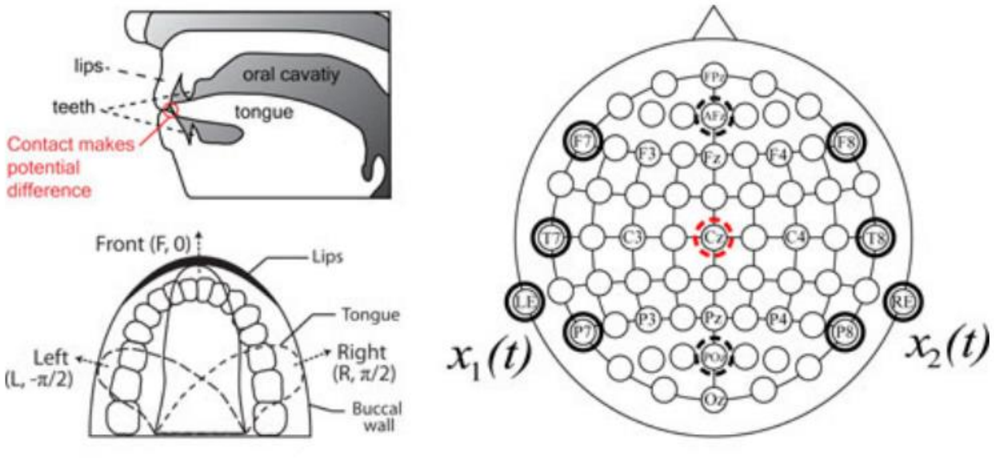


Figure 8: Mouthpiece for EMG-TCI [20]

The EMGTCI measures the EMG signals inside mouth, generated by the tongue movement in four directions, with the help of electrodes arrangement on the gum. After that the potential difference measured between electrodes is fed to the signal conditioning module before Analog to Digital conversion, then the computer classifies the tongue movement signal into a control command after further filtration. Electrodes are placed on extrinsic muscles which are related to tongue therefore it is easy to measure EMG signals related to tongue[20]. The electrode placed on the centre of gum is taken as a reference electrode and the potential difference measured between the reference electrode and other four electrodes is taken as EMG signal on those electrodes. The signal wires (AWG 22) used for electrodes have very small thickness value of 0.64mm so that they doesn’t cause any obstruction. The circuitry is attached on a mouthpiece shown in Figure 8 made for the lower jaw and the electrodes are positioned such that they touch the gum[20]. The EMG-TCI managed to classify tongue motion into five patterns using four EMG signal measurements but again fitting the system inside mouth requires invasive procedures, number of electrode placement inside mouth limits the number of classified commands and also the measurement system and computer are not connected wirelessly which can effect user mobility.

2.5.3 Tongue-Rudder: A Glossokinetic Potential (GKP) Based Tongue Machine Interface GKP-TMI



(a) (b)

Figure 9: GKP based TCI (a) tongue position (b) electrode placement [21]

GKPs are electrical activities that can be measured using electroencephalography along the human scalp. These are artefacts related to tongue movement. Tongue rudder measure these GKPs alongside the scalp as shown in Figure 9 and classify the tongue movements into defined control commands using Principal Component Analysis (PCA)[21]. G.USB amp device system with 5 Ag/AgCl electrodes was used for sensing the tongue movement and to deliver the data to the classifier on the microcomputer. One reference electrode was mounted on the head and two ground electrodes were mounted on forehead and then two electrodes were mounted on the locations from where the signals were recorded with respect to the reference electrode. The locations are left earlobe and right earlobe. The signals from the electrodes are then fed into the EEG amplifier which conditions them to make them readable for the machine. The conditioned signals are fed into the machine where they are visualised using EEGLAB topoplot tool and classified using Principal Component Analysis (PCA)[22]. GKP tongue machine interface coped to detect the tongue position and to interface tongue movement with a wheelchair but there is still a lot of space for improvement to implement the system in real life situation as the wheelchair shown deviation from given path in laboratory setup. Another problem with this interface is that it comes with some extra precautions of not moving eye balls which generates similar kind of signals and not moving chin which can displace electrodes. These provisions can be hard for patients who are already suffering and make it difficult for use.

2.5.4 Infrared based wearable Tongue controlled assistive Device

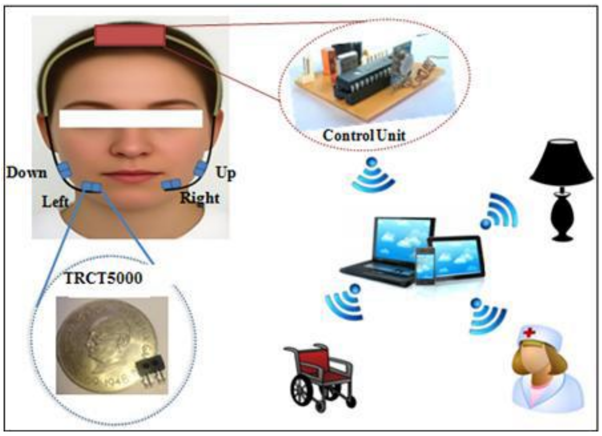


Figure 10: System architecture- wearable tongue controlled assistive device [23]

This interface uses an infrared sensor mounted bilaterally near cheeks as shown in Figure 10, when the tongue moves it changes the reflection intensity of the sensor which is converted into user commands through signal processing. The sensing element is TCRT5000 consisting of an IR transmitter and receiver packed together. Four of these sensors are mounted on the headset, two on each side of the cheek. According to the reflected light from cheek falling on the receiver, the sensor produces an output voltage.

When the tongue is in the neutral/resting position the output voltage from all the sensors will be fixed as threshold value. When the user needs to perform an action he pushes the cheek outwards, blocking the sensor hence changing the output voltage. This change in the signal is taken as the input to the controller module. The output from the sensors is amplified and digitised before further processing. Comparison algorithm is used to generate final user command, four outputs are compared to generate five commands in this presented research. The final command is then wirelessly transmitted to microcontroller on the other end installed on wheelchair, here a motor driver IC is also used to interface microcontroller output to the motors. Thus the wheelchair moves according to the commands received.

This research proposed a less intrusive interface but it can face some mechanical stability issues due to the headset worn in real life environment. Also the results accuracy is not discussed and the user commands are limited too.

2.5.5 Infrared Tongue Activated Beacon (ITAB)

An Infrared Tongue Activated Beacon (ITAB) is designed for receiving emergency signals from the critically ill patient. Information is traded via infrared signals to enable the sensors communicate with the alarm system. The signals does not interfere with other health care equipment. The signal receiver module is portable and has the flexibility to allow activation of different emergency systems. The sensing module includes push button, Light Dependent Resistor (LDR) and thermistor. Thermistor is added to activate alarm in dark conditions and night hours. A low cost PICAXE 8mm microcontroller employed to perform logic operations. ITAB employs synchronised working of two sub-systems; a transmitter which generates the infrared signal on users command and receiver which activates the alarm when signal is received[24]. The ITAB design successfully transmitted patient's request without being invasive although it has limited application but the idea can be carried to design minimally invasive TCI.

2.5.6 Infrared Tongue Supported Human Computer Interaction System (IRTSHCIS)

IRTSHCIS tracks the infrared light reflected by the tongue using Nintendo Wii remote, Figure 11 shows the process flow of the system. Then the signals are transmitted to computer via Bluetooth, there FreeTrack software is used to translate infrared data into usable output commands. A silicon tongue device usually worn by sleep apnoea patient is considered suitable for the design with a reflective tape attached on it. Nintendo Wii remote has built in camera which is use to collect reflected infrared light from tongue and it also have built in band pass filter which restricts detecting light sources outside desired wavelength. Based on the remote specifications of wavelength and distance between patient and camera, a good sizeable infrared array designed to output enough light intensity. Wii remote then transmits the data to PC by establishing Bluetooth connection. A Bluetooth dongle with specifications of V2.1 and class 1 easily recognised the presence of Wii remote due to Wii remote being classified as Human Interface Device[7].

FreeTrack software is employed to translate the received signals into cursor movements and outputs for other devices like wheelchair. FreeTrack is a multipurpose optical motion tracking software, used to accurately track sources of infrared light. The main aim is to track tongue tip movement and give patient control over mouse cursor which opens door to variety of communication to the world. A dwell clicking program also employed to provide the clicking functionality.

This system demonstrates that tongue computer Interaction can be implemented in less intrusive way. The system was able to generate good results with a design which was non-intrusive easy to use and low-cost. Though there is still a need to evaluate and enhance features like signal conditioning efficiency, machine learning/training, ease of learning. And the evaluation is required by both patients and caregivers.

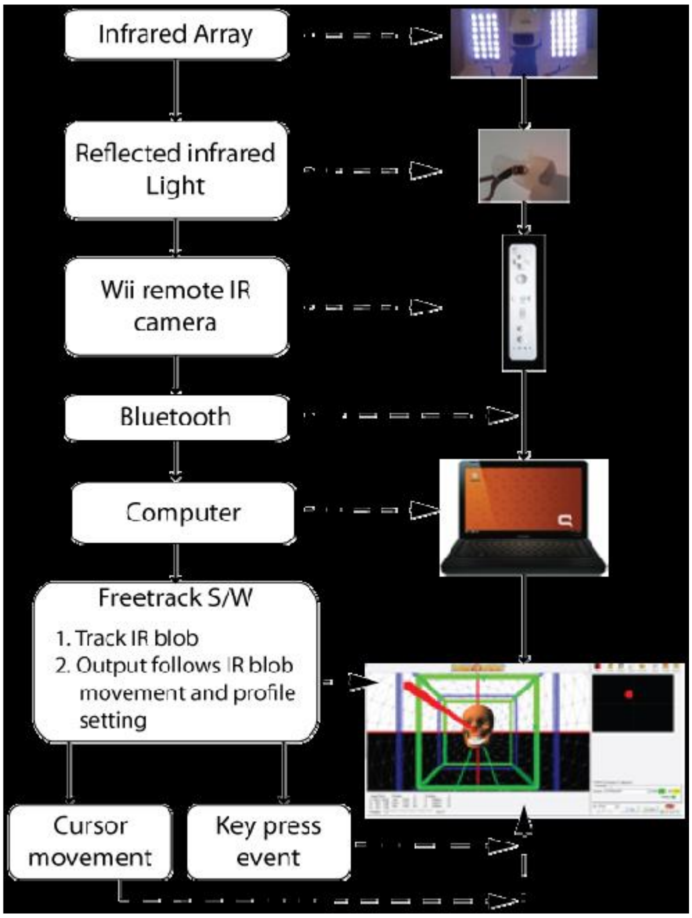


Figure 11: Process flow- IRTSHCIS [7]

2.5.7 Summary of Existing Tongue Computer Interfaces

Available TCI designs provide a good insight into using tongue as input modality to translate user intentions into control commands, Table 5 below summarizes the existing tongue position localization systems. However, most of them require us to insert cavity shaped hardware inside mouth which contains the sensors that translate motion into commands.

Such inside mouth installation may hinder with speech and eating, hardware is also very close to respiratory system so it imposes a lot of pressure for it to be hygienic. Accidental digestion is also a risk as there are very small parts involved in hardware. There is also a chance of intraoral trauma as electromagnetic signal and mechanical force both can hurt if their strength is over certain limit. These invasive TCIs require user to go through intrusive and expensive procedures and then huge maintenance is needed of the components installed. These unresolved issues related to intraoral complex environment are still keeping these existing systems away from commercial market.

Tongue Computer Interface System(s)	**Feature(s)**	**Observation(s)**
TDS	Magnetic Resistance	• The system shows promising control over wheelchair [18]. • The external design of the system, headset used for sensor mounting presents mechanical stability issues, which causes functionality issues in real life situation [18]. • The intra-oral design has yet to resolve the issue posed by signal transmission from inside mouth to the external system using transmission antennas.
EMG-TCI	EMG signal	• It achieved accuracy rates ranging from 72% to 90% [20]. • The interface is invasive and require mounting of electronics inside mouth. • Further Investigations can be made on the placement of electrodes and number of electrodes to achieve better accuracy and productivity.
Tongue Rudder	GKP signal (electrical signal)	• It detected the tongue position and translated them into commands to control wheelchair, however system's output showed deviation from the desired path ranging from 12.9° to24.2°. So it cannot be used in real life wheelchair situations [21]. • Extra care of not moving eyeballs is required because it generates similar kind of GKP signals, which can be hard for user. Also chin movement can displace electrodes that can affect the signals.

IRTSHCIS	Infrared light	• The system demonstrated tongue computer interaction with a minimally invasive, low maintenance, low cost design [7]. • It needs to go through rigorous testing under various sunlight conditions and then further clinical trials to be ready for real-life use.
Infrared based wearable tongue controlled assistive device	Infrared sensor	• This research demonstrated minimally invasive tongue computer interface. • It will need further development to be used in real life situations as the headset can cause mechanical stability issues while patient is out of testing environment.

Table 5: Summary of existing tongue computer interaction systems with author's comments

In the light of literature, presented research, aims to design a system which involves minimum intrusion to avoid complex feature space. This thesis used infrared proximity sensors that were installed outside of mouth to develop parametric models for tongue positions and combined with machine learning algorithms the presented system can translate tongue motion into useful commands.

Before going into technical specifications and design of this research, the following section will briefly discuss infrared radiation and its applications.

2.6. Infrared Radiation and its applications

Infrared radiation (IR), sometimes known as infrared light, is electromagnetic radiation (EMR) with wavelengths longer than those of visible light. It ranges from the red edge of the visible spectrum at 0.7 micrometres and extends to microwaves with a wavelength of 1000 micrometres. It is undetectable by the human eye, although IR of wavelengths up to 1050 nanometres (nm) s from specially pulsed lasers can be seen by humans under certain conditions. Most of the radiation emitted by a moderately heated surface is infrared; it forms a continuous spectrum. [25]

The Infrared region is further divided into three bands based on the wavelength.

- 0.7µm to 3µm is Near Infrared Region

- 3µm to 50µm is Mid Infrared Region
- 50µm to 1000µm is Far Infrared Region

2.6.1 Near Infrared Radiation (NIR)

It is closest to the visible light. A typical application of Near Infrared Radiation is Spectroscopy. Spectroscopy employs interaction of infrared light with the matter. The matter to be studied is presented with near infrared waves and any changes in the matter or how much light is absorbed by the matter is precisely measured to analyse the matter. Common applications of near infrared light in industry are: agriculture, food, pharmaceuticals, sports training, ergonomics, astronomy and neurology. [26]

NIR spectroscopy is extensively used to analyse brain function. Cerebral blood flow increases at the site where neural activity is activated and NIR spectroscopy can be used to monitor it. Figure 12 shows the reflection of near-infrared (NIR) radiation through the head.

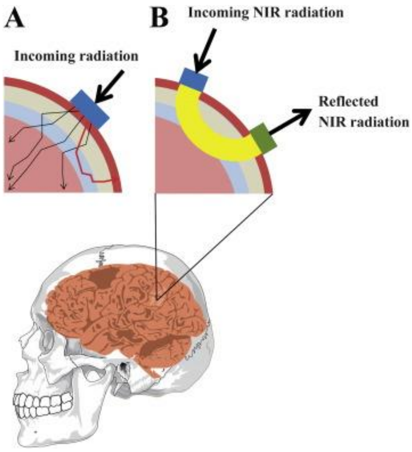


Figure 12: NIR spectroscopy illustration [26]

2.6.2 Mid Infrared Radiation MIR

Mid Infrared region ranges from 3 to 50µm. However, the mid-infrared spectral region of 2-20 µm contains strong characteristic vibrational transitions of many important molecules as well as two atmospheric transmission windows of 3-5 µm and 8-13 µm, which makes it crucial for applications in spectroscopy, materials processing, chemical and bimolecular sensing, security and industry.

2.6.3 Far Infrared Radiation

The Far-infrared region is the largest of the three regions; the wavelengths of this region vary from 50 up to 1000 micrometres. The Far-infrared region is of particular use to the medical industry due to its ability to penetrate, refract and reflect human tissue [26]. Far-infrared light penetrates the skin down to the subcutaneous tissue. This helps the blood vessels within capillaries to dilate, improving blood circulation within the body. That improvement transfers oxygen to joints, therefore allowing injured muscles to repair faster due to stronger blood flow. [27] Far-infrared therapy is one example of above described procedure. Figure 13 below shows the effects of high infrared therapy on blood circulation overtime, red area shows the blood flow. The photograph is taken by a thermal imaging camera another example of infrared light application.

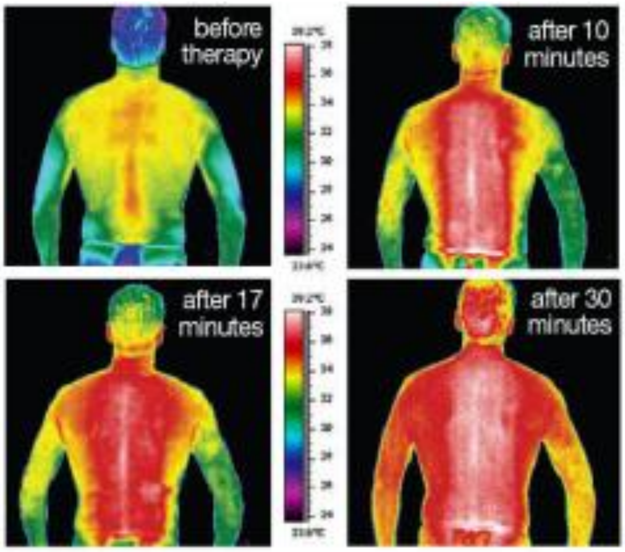


Figure 13: Effects of thermal therapy [27]

2.6.4 IR sensor

An IR sensor is an electronic device that detects IR radiation falling on it. An IR sensor comprises of the emitter and the receiver circuit as shown in Figure 14. The emitter is an IR LED and the detector is an IR photodiode. The photo-diode’s resistance and output voltage change in proportion to the IR light received. This is the underlying working principle of the IR sensor.

There are generally two light emitting-receiving modes for IR sensors; direct mode and reflecting mode. In direct mode, the IR LED is placed in line of a photodiode with no obstacle in between. In indirect mode, both the diodes are placed side by side with an opaque object in front of the sensor. The light from the IR LED hits the opaque surface and reflects back to the photodiode. [29]

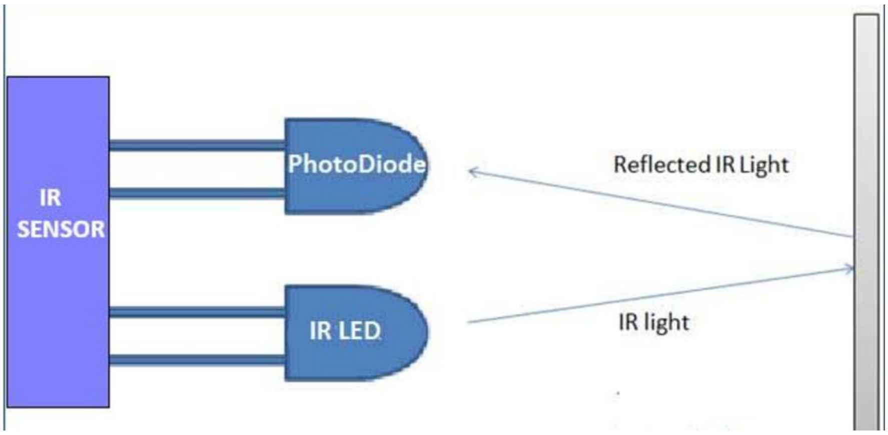


Figure 14: IR sensor schematic [28]

IR sensors are used in various fields. Following are the few applications;

2.6.4.1 Proximity Sensors

Proximity sensors employ reflective incidence principle. The photodiode receives the radiation emitted by the IR LED once reflected back by the object. Closer the object, higher will be the intensity of the incident radiation on the photodiode. This intensity is shown as the change in voltage of the receiver circuit that can be used determine the distance. Proximity sensors are commonly used in touchscreen phones. [28]

2.6.4.2 Line Follower Robots

Line followers employ reflective or non-reflective incidence. The IR is reflected back to the module from the white surface around the black line. But IR radiation is absorbed completely by black colour. There is no reflection of the IR radiation going back to the sensor module in black colour. Then the signal is sent to the controller circuit that takes the decision according to the logic built in the robot.

2.6.5 IR sensor in assistive technology

2.6.5.1 Head mouse

This research has presented a head-controlled assistive wireless mouse for users suffering from motor disabilities in their hands and fingers. The control of the mouse cursor position is done entirely by head tilting, and clicking is done by either inflating the cheek or poking the tongue on the cheek. The system uses a pair of reflective IR to detect relative collar-to-under cheek distances for 2D cursor positioning and a pair of force-sensing resistors (FSR) for clicking. [30]

The research proposed controlling the cursor on the screen using the signal change observed by changing the distance between the IR sensor and the user's head (chin). In resting position, two sensors approximately receive the same amount of IR signal due to symmetry. Tilting down the user's head brings both sensors closer to the surface of reflection, resulting in a stronger signal. Likewise, tilting up the head weakens the reflection received by both sensors due to the longer distance. When the head turns to the right, the left sensor sees a weak reflection from the left side of the chin, but the right sensor sees little change in the reflection since the chin is still above the receiver. Thus, a weak signal on the left sensor and a strong signal on the right sensor indicates a cursor movement to right.

2.6.5.2 IR sensor based Tongue controlled assistive device

Discussed in section 2.5.4

2.6.5.3 Infrared Tongue Supported Human Computer Interaction

Discussed in section 2.5.6

2.7 Chapter Summary

In summary, this chapter signifies the further exploration in the tongue computer interaction area. Number of people that can benefit from the research and the lack of available assistive systems in the market justifies the presented research. Tongue inherent capabilities make it the best option for being used as input modality for tongue computer interaction system designed for people suffering with quadriplegia. Infrared radiation is widely in use by biomedical industry and has the capability to react to human tissues and muscles. The biggest advantage of using infrared is ability to design a less invasive and easy to use and maintain system.

Next section will discuss the requirements and methodology for this research.

Chapter 3

System Requirements and Scope

3.1 Chapter Introduction

This chapter discusses the requirement criteria for the system. It then reviews the scope of work and design methodology for the presented research.

3.2 Research Problem

Design and implement a low-cost, minimally invasive, easy to use Infrared activated Tongue computer interaction system.

3.3 Requirements Analysis

The requirements are derived based on the relevant literature and the investigation on the past research done in the area of tongue assistive technology. The system design should meet the following requirements to prove that infrared proximity sensors can be used in a design of a minimally invasive, easy to use interaction system.

1. It shall generate discrete, repeatable, reliable output
2. It shall be minimally-invasive
3. It shall be easy to use
4. It shall be capable of effective computer Interaction
5. It should be resilient to interferences
6. It shall require low physical effort

3.3.1 System Design Specification

3.3.1.1 Discrete Signal Generation

The system should be able to generate a reliable, repeatable, distinct signal for each tongue movement/position.

With each movement of the tongue the medium should be able to generate and capture different level of voltages. The change in voltages for different positions will define feature for that position. Therefore it is important to generate distinct and repeatable output for each position. This will help the designers to translate the user voluntary movement into defined user needs. It will improve the reliability of the communication device.

3.3.1.2 Minimally invasive

The system should be minimally invasive.

The investigation into the existing tongue computer interaction technologies has observed that all of them are highly invasive. This work focuses on the user’s comfort thus the system should not require them to go through intrusive procedures to get installed. And it should focus on recording external feature changes when the tongue is moved. It should not raise hygienic concerns.

3.3.1.3 Easy to learn and Use

The system should be easy to learn and use.

As our target demography is fragile, severely ill patients, the system should only require small input from them to create desired output. It is also presented in the literature that the muscle should not use more than 50% of its maximal strength.

The system should take less amount of time for the user to become proficient.

3.3.1.4 Effective Interaction

The system shall achieve effective interaction with computer

The system is proposed to be used by rehabilitation centres and assistive system designers. Rehab services and assistive systems both widely use computer interaction to achieve their respective outcomes. Therefore the system should be able to demonstrate effective control of computer cursor.

3.3.1.5 Resilient to interference

The system should be resilient to environmental interference.

This is a highly desirable requirement. As the users are severely ill patients they might be relying on other medical equipment therefore this assistive system should not interfere with other equipment in the surrounding. For its own optimal performance the system should be resilient to any noise interference from the surrounding.

The specification defined above will be considered throughout the design process.

3.3.1.6 Low physical effort

The system should require low physical effort to effectively operate.

According to studies, to reduce the risk of repetitive strain injuries the tongue must be operating at less than 50% of its maximum strength capacity. Therefore, It can be suggested that the interactive part of the tongue communication system should be able to operate with as minimal force as possible

The design can be used efficiently and comfortably, and with a minimum of fatigue.

3.4 Scope of Work

The scope of work for the presented research can be divided into following four categories;

3.4.1 Design IR sensing module to achieve external feature space for tongue position localization

The focus areas to complete this task are;

- Reviewing sensor properties
- Discrete signal for each position (Reduce light interference)
- Sensor array configuration
- Size of the sensor array
- Installation mechanism

3.4.2 Generate parametric tongue position models for six position

The key tasks are;

- Generate Discrete infrared feature for each tongue position
- Software development to record parametric model for each tongue position

3.4.3 Train Classifier for tongue position classification

Tasks included are;

- Train classifier using parametric tongue position models
- Classifier performance review

3.4.4 Real-time Implementation Trial

- Use trained classifier to achieve effective tongue computer interaction
- Software development to control cursor based on classifier predicted values

3.5 Design Methodology

Engineering design methodology is employed to design, implement and evaluate the system. Figure 15 below shows the process.

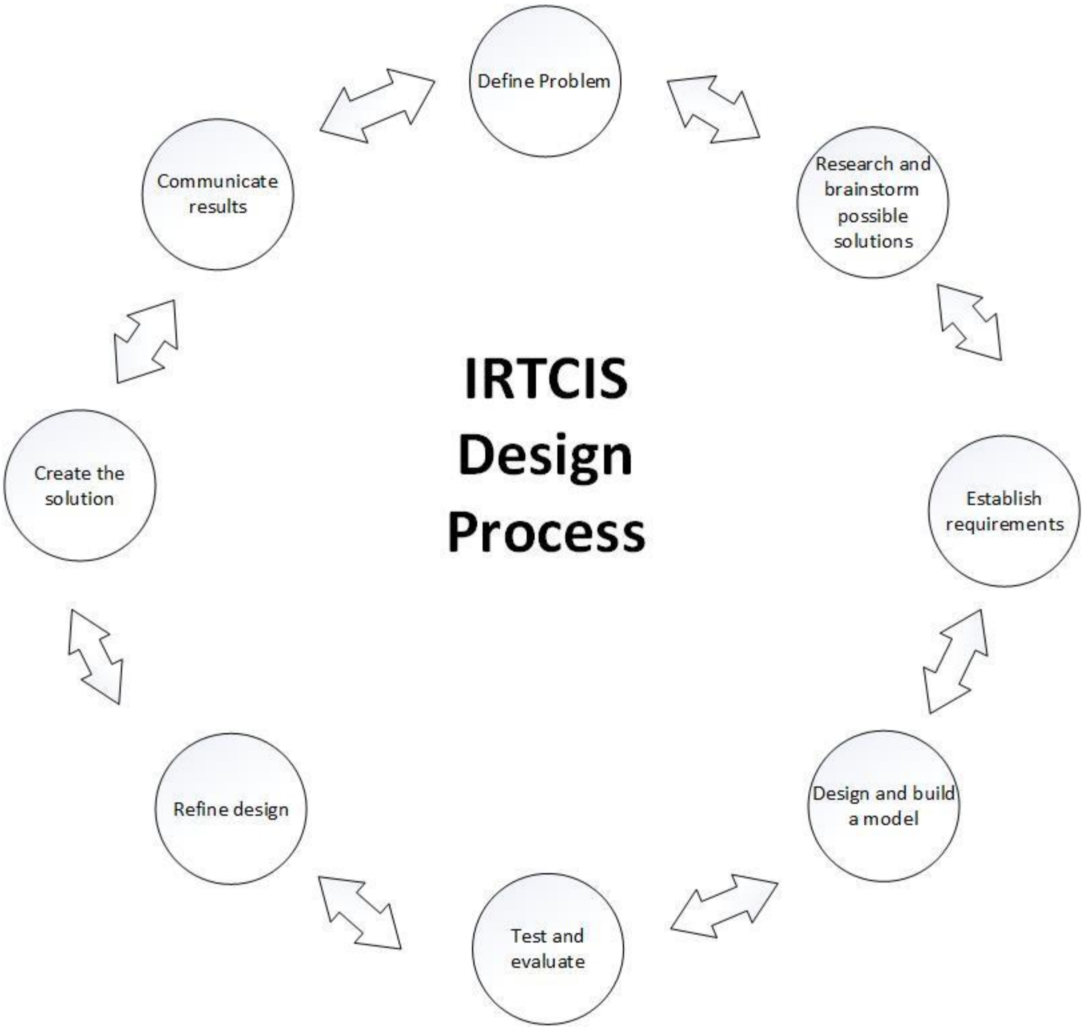


Figure 15: Design Methodology [31]

System specifications are derived as per the needs. The concept is tested against the criteria to meet the needs. Improvements are made constantly to the mechanical and software design to comply with the requirements. Final implementation is presented and future work is proposed.

3.6 Chapter Summary

This chapter discussed system requirements and derived the design specifications to be able to meet the research objective. It showed the iterative design methodology employed to achieve continuously improved product.

Next chapter will discuss the design phase in detail.

Chapter 4

Infrared Activated Tongue Computer Interaction- System Design

4.1 Chapter introduction

This chapter will discuss the detailed design of the Infrared activated Computer Interaction System (IRTCIS). It will address the hardware design and the software implementation of the system. Experimental results have been discussed to display performance of the system design.

4.2 System Configuration

Figure 16: Infrared activated tongue computer interaction system

Figure 16 above shows the system block diagram. The system design employs the IRLED sensor array wore in front of mouth with the help of 3D printed mask as a sensing unit. The output signal of each sensor is sent out to the microcontroller via USB cable and the same connection provides the power to the sensors. The controller reads the change in reflected light from each sensor and records it as an array of six variables for each position. Then the Signal array is transferred to the computer where the software assign user defined response to each set of variables for specific position. This generates our parametric tongue models for six different position. The parametric tongue models are then used to train a classifier which then predicts specific command for each tongue position as per the parametric models.

4.3. Hardware Design

4.3.1 Sensor Array Design for extracting external features for tongue movement.

The approach to use infrared sensor and arranging them in array is based on the concepts presented by Infrared based wearable tongue controlled assistive device [23]and Infrared Tongue activated beacon [24] respectively.

The following section will discuss the key elements explored to achieve the final sensor array design;

- IR Proximity sensor GP2Y0A41SK0F
- Size and Orientation of the sensor array
- Reduction of Light interference

4.3.1.1 Infrared Sensor- Sharp GP2Y0A1SK0F

Infrared distance measuring sensor GP2Y0A41SK0F [32] is used to detect the tongue position in the presented research. It was selected due to its compact design consisting of an integrated combination of Infrared emitter, position sensitive detector and signal processing circuit all in one small package. Also the reason that the variety of the reflectivity of the object, the environmental temperature and the operating duration are not influenced easily to the distance detection because of adopting the triangulation method.

The sensor outputs the voltage corresponding to the detection distance. The sensor characteristic curve is shown in the Figure 17 below. It shows that the voltage decreases with the increase in distance, between sensor and the target object, within the useable range.

For our application this change in corresponding output voltage for different position of the tongue is recorded and used as external feature of tongue movement.

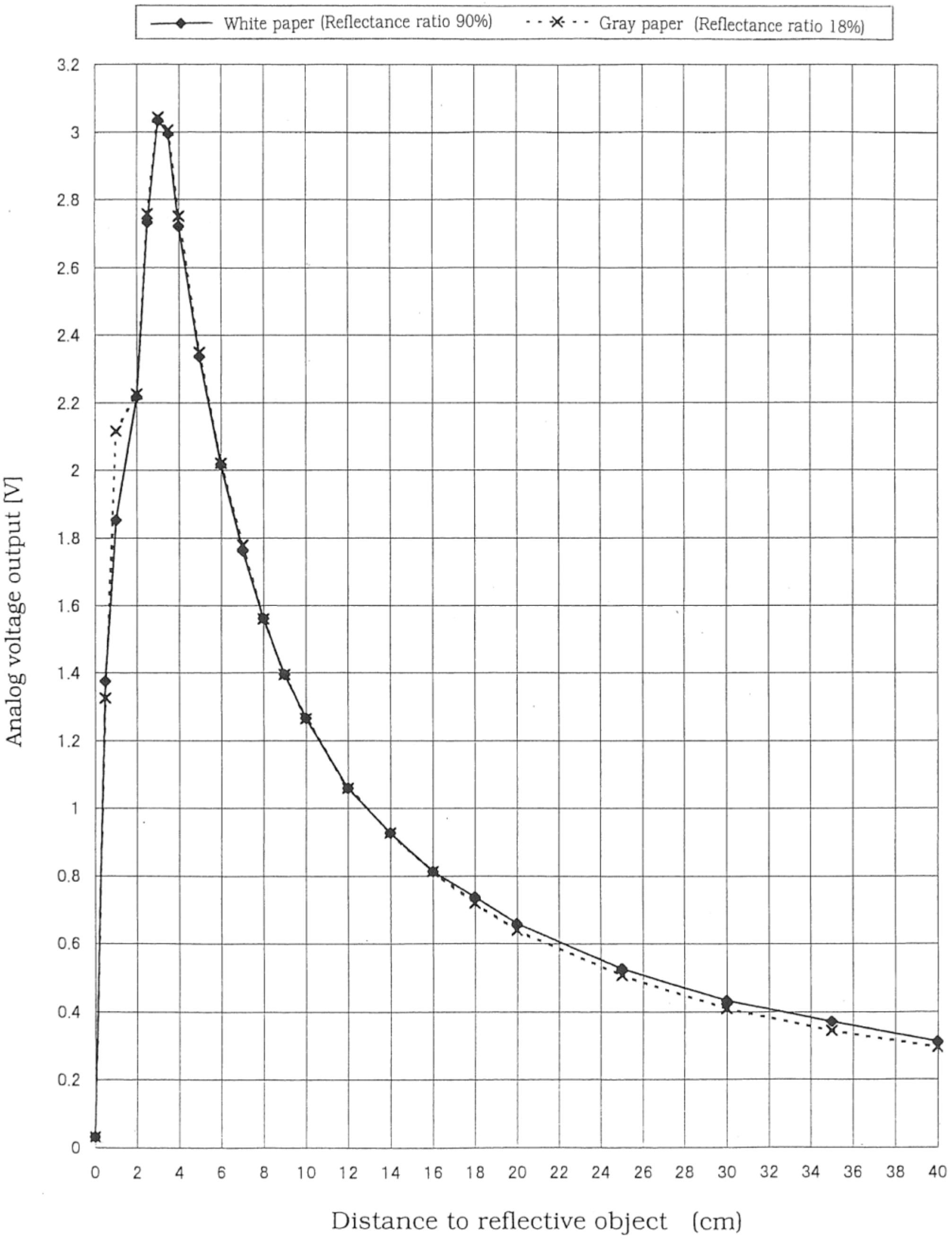


Figure 17: Sensor output distance characteristic curve

The design specifications of the infrared proximity sensor array was determined by its application and the sensor characteristics. Firstly the array should be small size so that the user's does not need to extend the tongue far from the comfort zone. Also the sensor response time should be quick so that the user does not have to keep the tongue extended for longer period of time. Things like array shape, number of sensors, and signal de-noising were considered and explored during the IR array design.

4.3.1.2 Light Interference

Light interference can be caused by diffused light present in our environment and cross-over talk between the sensors. The presented system's environment will always consist of natural or artificial light that can interfere with the intensity of the reflected light coming from target. Therefore insulator is required to reduce the light interference. Also the IR beam propagated from the sensor can cross-talk with the beam from neighbouring sensor causing interference.

To reduce the light noise, this research used FPR-01 Hi-tack flocked light trap material[33] as an insulator. It is generally used in astronomical telescopes for same purpose. It was installed on the sensor walls to absorb any unwanted light signal. It helps emit direct light beam and reduce the light reflected back to the detector hence maximising the signal ratio reflected back from target.

Protostar light trap material shown below in Figure 18 is designed for the visible spectrum (~400-700 nm) where it absorbs over 99% of incident light. It also attenuates in the near-IR and near-UV by over 80%. Figure 19 presents the reflectivity curve of Protostar light trap material, it behaves similar to black body in visible range and absorbs more than 80% in Infrared range. Hence it is best fit for our application to reduce majority of light interference.

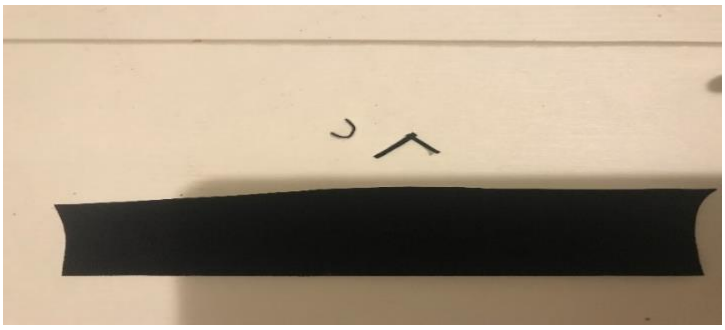


Figure 18: Hi-Tack flocked light trap sheet

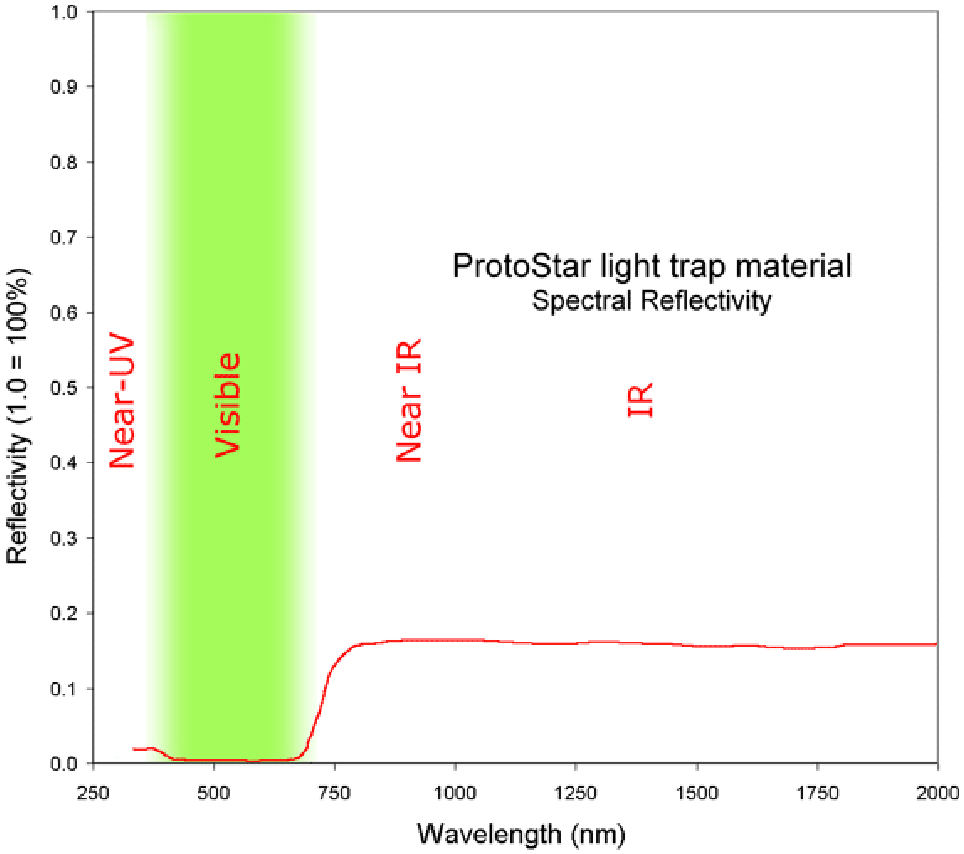


Figure 19: Reflectivity curve of Protostar light trap material

This section will discuss the experimental results that show the use of Protostar light trap material can reduce light interference and hence can produce distinct, repeatable output signal for specific tongue positions. The light interference can cause unwanted change to the output signal with no change in target and input conditions. Therefore light insulator is used to achieve reliable output signal.

IR led emits light all around it which then reflected back from any surfaces that come in the way and can impact the detector readings. To reduce this noise, light trap sheet was glued around the IR led emitter onto the sensor. The addition of light absorbent sheet helped achieve consistent output signal for every sensor for each tongue position. The Figure 20 below shows the readings from one sensor; the distance between the target and the sensor and all the environmental conditions are unchanged. The horizontal axis of the chart shows sensors readings taken every 500ms and vertical axis shows sensor output recorded as byte value. The chart shows that sensor once fitted with insulator produce less variance in output value. Hence consistent, reliable, repeatable signal. It is achieved by attenuating present interference caused by diffused light or sensor cross-over talk.

Further to the Protostar light insulator, an enclosed mask design will be used to block the ambient light present in the environment.

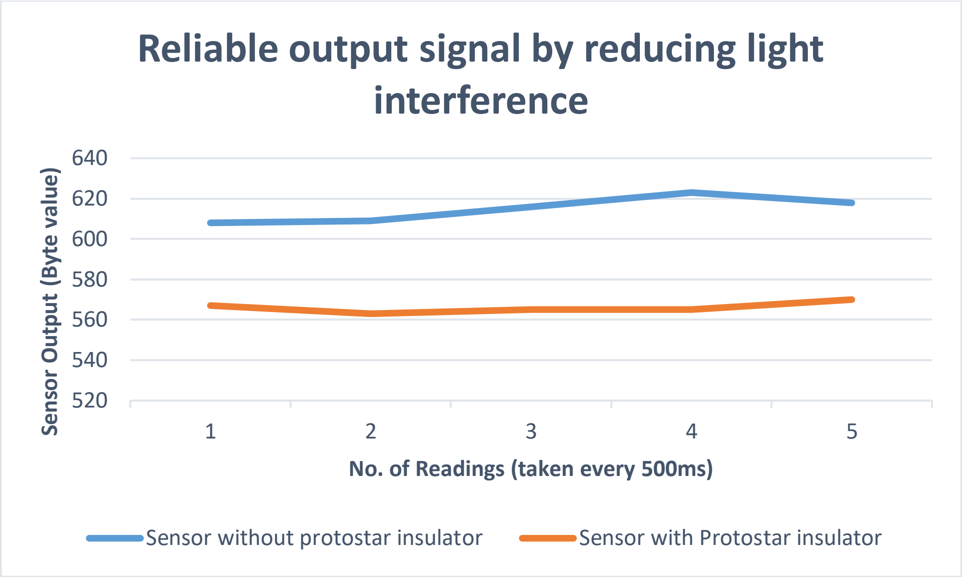


Figure 20: Effect of Protostar insulator- output not influenced by light interference

4.3.1.3 Size and Orientation of Sensor array

A rectangular shape sensor array was designed. A rectangular orientation was chosen to make it similar to aspect ratio of standard display screen. Aspect ratio is the proportional relationship between the width and height of the display. As the system propose tongue computer interaction and aims to achieve tongue localisation onto a computer screen, the sensing array was designed to be similar to aspect ratio of screen, hence rectangular shape. Study done by Masood Khan and Rohan Quain at Curtin University “Portable tongue-supported human computer interaction system design and implementation” [16] also used rectangular infrared array to sense the tongue movement.

The 2*3 array (shown in Figure 21) was chosen as it made the right size to fit in front of the user’s mouth, hence allowing the user to not extend their tongue far from their comfort zone. 3*4 orientation was also explored, however the array was becoming bigger and bulkier which was not suitable to wear for people living with physical disabilities.

The 2*3 array is compact and lightweight. Figure 21 below shows the development of the senor array. Left side shows the array used during the design phase, a card board was used to mount sensors. Right side show the final sensor array on printed circuit board.

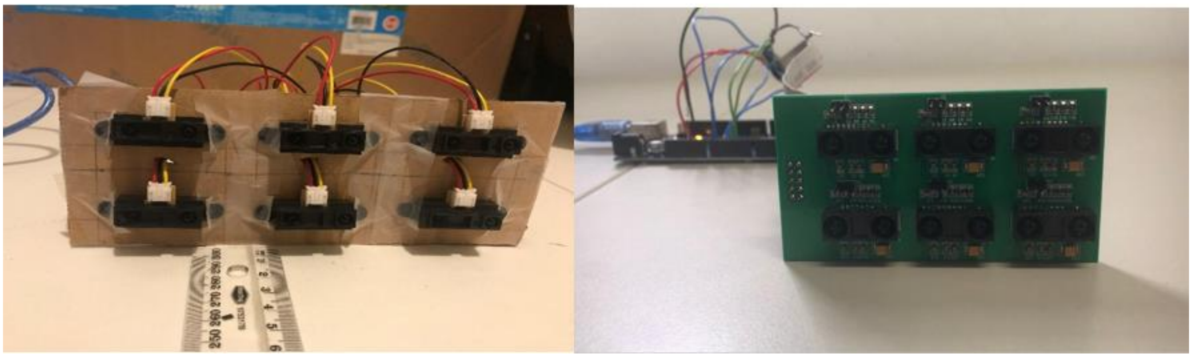


Figure 21: Infrared Proximity Sensor Array

Presented sensor array, follows the characteristic curve of Sharp distance sensor. And it generate repeatable, reliable output for different target positions. Figure 22 below shows the useable range for our application, a rough white surface is used for this experiment. Although the sensors has measuring range of 4 to 30 cm, our design will focus on 4 to 10 cm(s) because it is designed and developed with the intent to serve tongue computer interaction for physically disable people. The design should allow users to operate system with small movements of tongue. We will further discuss the array behaviour in next section.

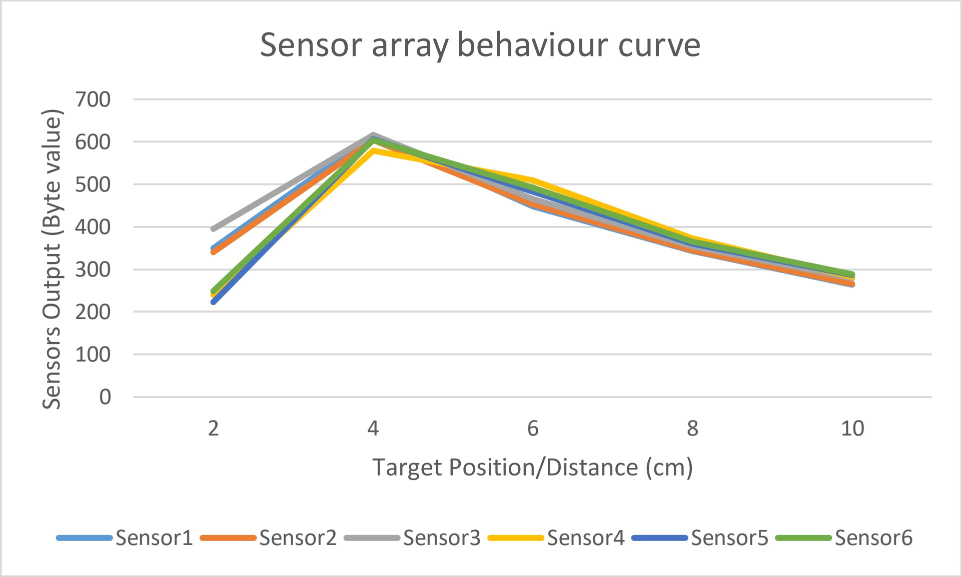


Figure 22: Sensor array characteristic curve

4.3.2 Wearable 3D mask- sensor array placement

For placing the array in front of mouth, a wearable 3D printed mask shown in Figure 23 was developed. The idea is inspired by the commercially available safety mask however the size of the mask is calculated as per the sensor array size and optimum sensing distance shown in Figure 22. A 10.5L x 7.5W x 10 H size mask was designed and printed at Curtin university lab. The Length is 10.5cm to fit up the 2 * 3 sensor array. The width is 7.5cm that let the mask sit on nose and chin. The depth of the mask is kept 10cm.

The mask was used for placing the array to further block the unwanted light present in the system’s environment. A black colour mask was used to absorb light as much as practicable. It not only help block the ambient light in the environment, it also absorbs the light falling on it. Hence the sensor receives the light reflected from tongue and mouth only.

The mask used elastic strap to make it wearable. A soft foam sheet was attached to the nose fit area to make it comfortable to use.

Figure 23: Mask to hold sensor array

This concludes the design of hardware component of the research, next section will discuss the software development of the presented research.

4.4 Software

4.4.1 Architecture

The Figure 24 below presents the software functional block diagram of this research. The software development comprises of three key features. These features are reading and recording data, creating training dataset and classifier training. The Data recorder section reads the sensor signals into an array variable. Tongue movement changes the output signal of the sensor array. This can be referred as feature array the defined tongue position. The next block assigns the response to recorded arrays to create training dataset. The response is assigned as per the user defined requirements. This dataset is one of the main contributions of this research. It creates the user-specific parametric tongue models for the user-defined positions. Third block is used to train Linear Discriminant Analysis (LDA) Classifier. The software system was coded in Arduino and MATLAB.

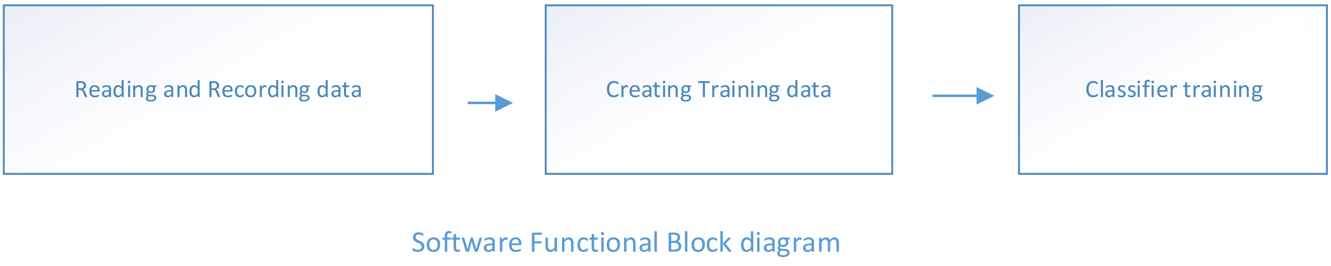


Figure 24: Software Block diagram

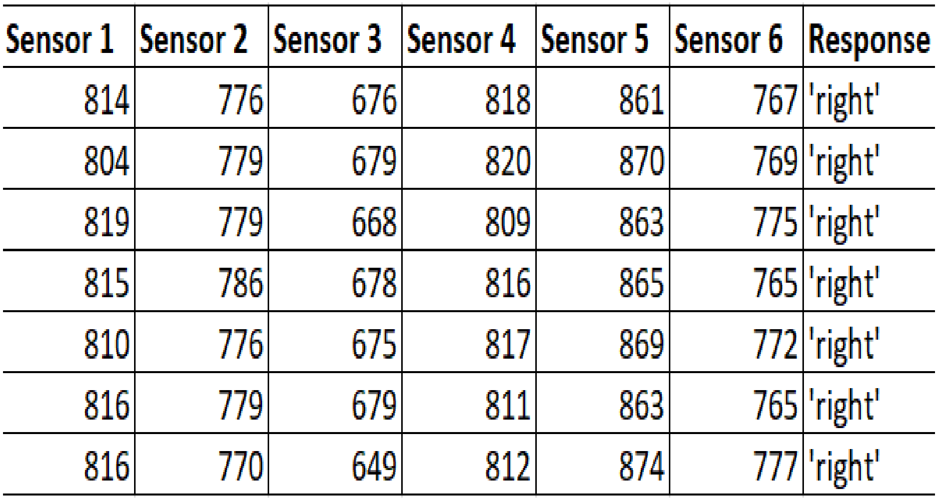
4.4.2 Code for generating feature array for user-defined tongue positions

Code shown below in Figure 25 used to record sensor readings and sends them to the host computer. Arduino microcontroller is used as a communication module between senor array and host computer. The training dataset is recorded for each of the six tongue positions and then the user-defined response is assigned to dataset for each tongue position. Example of parametric tongue position model for tongue movement to user’s right is presented in Figure 26, refer to Appendix B Parametric Tongue Position Models- Training dataset for classifier for complete dataset.

```
int i=0;
int j=0;
int k=0;
int sens[6] = {A0, A1, A2, A3, A4, A5};
int output[6]={0};
int toutput[6]={0};
int avgsen[6]={0};
int readings= 20;
void setup() {
  // put your setup code here, to run once:
Serial.begin(9600);
}

void loop() {
  // put your main code here, to run repeatedly:
for (j=0; j< 6; j++){
  for (k=0; k<readings; k++){
    output[j]=analogRead(sens[j]);
    toutput[j]= toutput[j] + output[j];
  }
  avgsen[j]= toutput[j]/readings;
  toutput[j]=0;
}
for(j=0; j<6; j++){
  Serial.print(avgsen[j]);
  Serial.print("\t");
 }
```

Figure 25: Code for recording sensor output



Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Response
814	776	676	818	861	767	'right'
804	779	679	820	870	769	'right'
819	779	668	809	863	775	'right'
815	786	678	816	865	765	'right'
810	776	675	817	869	772	'right'
816	779	679	811	863	765	'right'
816	770	649	812	874	777	'right'

Figure 26: Training dataset for tongue movement to user's right

After recording the tongue position parametric models for all six position, classifier is trained on the dataset to predict tongue position for real-time implementation. Next section will provide brief introduction to machine learning before presenting classifier developed by this research.

4.4.3 Machine learning

Machine learning is a data analytics technique that teaches computers to learn from experience. Machine learning algorithms use computational methods to "learn" information directly from data without relying on a predetermined equation as a model. The algorithms adaptively improve their performance as the number of samples available for learning increases.

Machine learning finds patterns in the data that generate insight and help you make better decisions and predictions.

Machine learning helps when you have a complex task or problem involving a large amount of data and lots of variables, but no existing formula or equation. Some examples are face recognition, motion detection, load forecasting, predictive maintenance etc.

Machine learning uses two types of techniques: supervised learning, which trains a model on known input and output data so that it can predict future outputs, and unsupervised learning, which finds hidden patterns or intrinsic structures in input data[35].

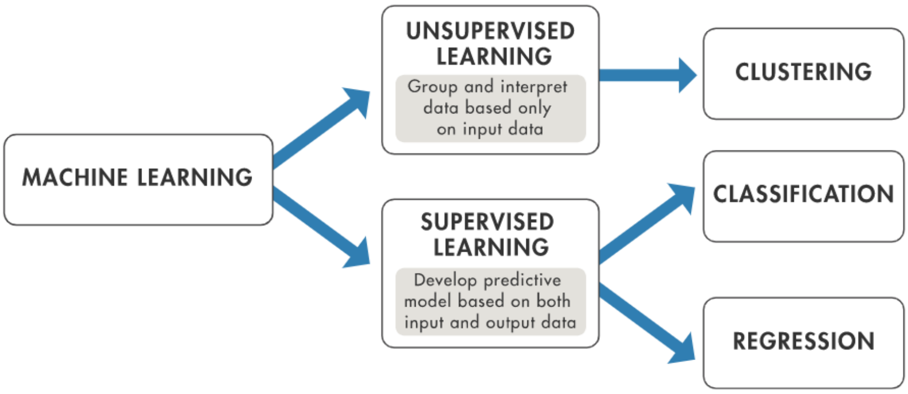


Figure 27: Machine learning techniques [35]

The Figure 27 above shows that classification is the category of supervised learning. Supervised machine learning builds a model that makes predictions based on evidence in the presence of uncertainty. A supervised learning algorithm takes a known set of input data and known responses to the data (output) and trains a model to generate reasonable predictions for the response to new data. Use supervised learning if you have known data for the output you are trying to predict. Supervised learning is the most common type of machine learning algorithms.

Classification techniques classify input data into categories. Use classification if your data can be tagged, categorized, or separated into specific groups or classes. A binary classification model has two classes and a multiclass classification model has more. Common classification algorithm includes; Support Vector Machine (SVM), Naïve Bayes classifier, discriminant analysis, neural network.

4.4.4 Classifier Training

The classifier design uses the dataset presented in Appendix B Parametric Tongue Position Models-

Training dataset for classifier. Six different positions are classified into six output categories. The classifier will use the known input data and known output data to train an algorithm to predict output response for future input values. To evaluate which classification technique is suitable for our application, we used a client software to test the accuracy of the different classification techniques. The client software used for this research work is MATLAB. The Classification Learner can run multiple classification techniques on the input data and shows the accuracy of each technique for comparison.

LDA was used for final implementation because the system used linearly arranged array and showed linear variance in the sensor outputs.

Linear Discriminant Analysis (LDA) is a dimensionality reduction technique that is commonly used in pattern recognition and machine learning. The goal of LDA is to project a dataset onto a lower-dimensional space while maintaining the class separability as much as possible.

LDA is a supervised learning method, which means that it requires labelled training data to find the projection. The method finds a linear combination of the features that maximizes the separation between the different classes. The resulting linear combination is then used to transform the original data into a new feature space, where the classes are more easily separable. One of the main advantages of LDA is that it is efficient and easy to implement.

4.4.4.1 Classification matrices and interpretation

The Classifier is trained with 95.4% accuracy. Next step is to analyse the classifier performance and check accuracy scores using confusion matrix. The confusion matrix plot helps understand how the currently selected classifier performed in each class and identify the areas where the classifier has performed poorly.

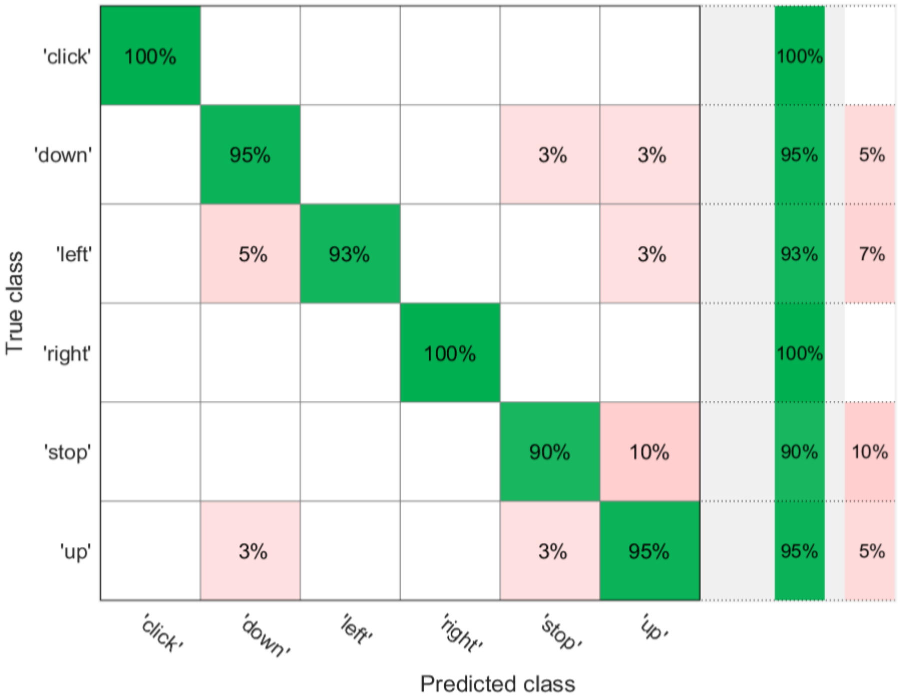
In Figure 28 below the Model is the trained Linear Discriminant Analysis (LDA) classifier, it is showing the classifier's performance per class. The last two columns on the right summarises the performance per class. The green and red column shows the true positive rates and the false negative rates respectively.

For the LDA classifier trained using the parametric tongue models, the top row shows all class readings with true class "Click". The columns show the predicted classes. In the top row, 100% of the click positions are correctly classified, so 100% is the true positive rate for correctly classified points in this class, shown in the green cell in the True Positive Rate column.

In second row from top, 95% of the down positions are correctly classified, giving us the true positive rate of 100%. The other positions in the down row are misclassified, 2.5% (the plot is showing the round off figure of 3%) of the positions are incorrectly classified as from stop class and 2.5% (3% shown in figure, rounded off figure) are classified as from up class. 5% is the false negative rate for incorrectly classified positions in this class, shown in the red column.

In fifth row from top, 90% of the stop positions are correctly classified and 10% are classified as up position, giving us the true positive rate of 90% and false negative rate of 10%.

Overall, the classifier has accuracy of 90% and above to correctly classify the true class of position.



	'click'	'down'	'left'	'right'	'stop'	'up'		
'click'	100%						100%	
'down'		95%			3%	3%	95%	5%
'left'		5%	93%			3%	93%	7%
'right'				100%			100%	
'stop'					90%	10%	90%	10%
'up'		3%			3%	95%	95%	5%

Figure 28: Confusion Matrices- true positive and false negative rates

We discussed the true positives and false negatives for each true class, now let's analyse how many times a predicted class was a false positive. In our problem, false positives are also important as they also add to the misclassifications that can lead to less effective computer interaction.

The Figure 29 below shows the Positive Predictive Values and False Discovery per predictive class. In the rows underneath the matrix, Positive predictive values are shown in green for the correctly predicted points in each class, and false discovery rates are shown below it in red for the incorrectly predicted points in each class. Positions click, left and right have 100% rate of positive predictive values. Second column from the left shows the classifier performance for the down class. 93% of the predictions are correctly classified but 7% of the predictions were false positives, it was other (left and up) positions classified as down. For class up at the right most column, 86% of the predictions were true positives while 14% of the predictions were other position classes misclassified as up.

Overall, the classifier has three predicted classes with zero false discovery rate, two classes with false discovery rate below 10% and only one class with 14% false discovery rate.

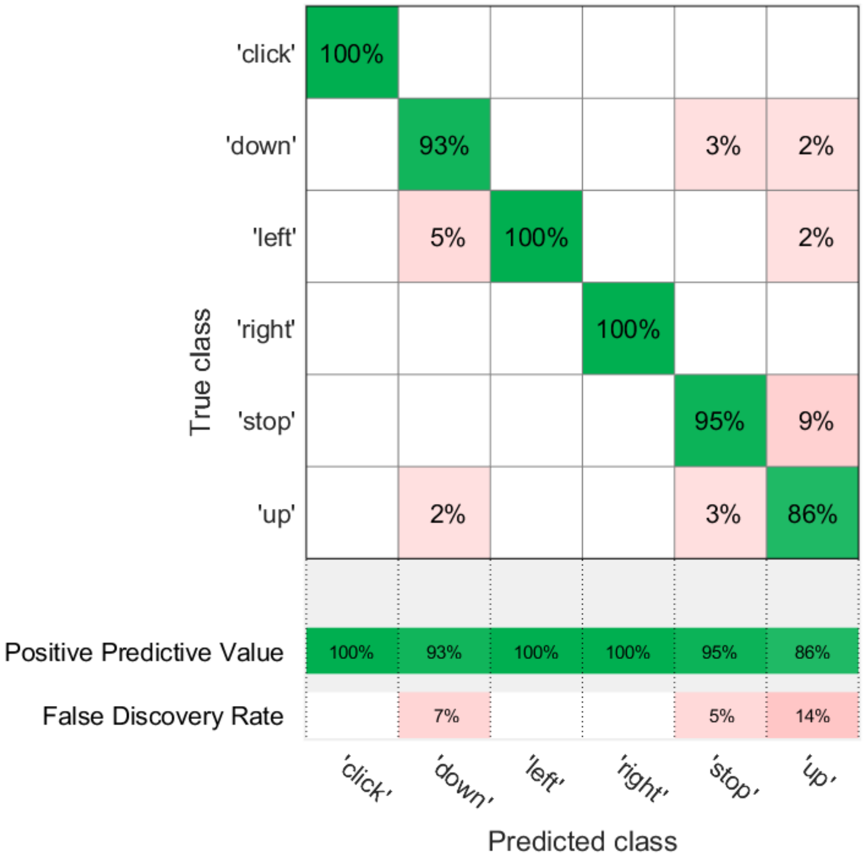


Figure 29: Confusion Matrices- positive predictive and false discovery rates

4.5 Process

A 2 x 3 sensor array is designed and wore in front of user’s nose and mouth with the help of a 3D black mask. Sharp GP2Y0A41SK0F distance measuring sensor is used. It is used to detect tongue movement and generate feature array for six different tongue position. User-defined response is assigned to each feature array for all six positions which gives us parametric tongue position models. These parametric position models are used as training dataset for our classifier. Trained classifier provide the capability to localise tongue movement into cursor movement on the screen. Table 6 below shows all the components involved in design process

ID	Components
1.	IR Proximity Sensor SHARP GP2Y0A41SK0F

2.	Microcontroller Arduino ATmega2560
3.	Wires
4.	Host machine with Arduino and MATLAB codes
5.	Mask

Table 6: System hardware components

4.6 Data Plan

This section states the contents and structure of data collected during the research work. It also mentions the storage and safeguarding agreement for the data.

The research data comprise of; results from experiment carried out to design the IRTCIS sensing unit, data analysis on the experiment results, data table for parametric tongue position models for six tongue positions, Arduino and MATLAB scripts, drawings of 3D mask, and photos from experiments.

For the duration of the project, the physical data was stored in the locked cabinet with the research student and digital data is saved in the password protected laptop and backed up to an external hard drive. It will also be stored in Curtin's research drive and retained there for appropriate timeframe.

4.7 Chapter Summary

This chapter presents the design of the Infrared activated Tongue Computer Interaction system. It discussed the detailed design of the sensing unit used in the system and presented the dataset recorded for six different tongue positions. Then it discussed the process of training an algorithm to classify recorded tongue position models into defined classes. LDA classifiers used for final design, it showed 95.4% accuracy to predict correct class category.

The next chapter will present the final implementation of the system and will conclude this research work.

Chapter 5

Infrared Activated Tongue Computer Interaction- System Trial

5.1 Chapter Introduction

This chapter presents the implementation of the Infrared activated tongue computer interaction system to achieve cursor control on the screen. It discusses the trial process and execution setup, and demonstrates that the developed system can achieve tongue computer interaction and has the potential to be implemented as assistive technology.

5.2 Trial Objective

The trial objective is to control cursor movement on screen using infrared activated tongue computer interaction system developed at Curtin University. The aim of this trial is to test and prove that the presented system has the potential to be implemented as assistive technology for physically disable people. If the user can achieve cursor control using this system, it proves its capability to be implemented in assistive technology. Because with cursor control you can control devices in your environment like light, doors, alarm. This research is a progressive step towards using infrared activated, minimally invasive tongue computer interaction in assistive technology. It can also be used to design rehabilitation system for people suffering from dysphagia.

5.3 Trial Process

The system is used by the author to control computer cursor. This was achieved by sensing tongue movement and classifying that tongue position into user defined categories. Further to what has been discussed in previous chapter, this trial adds another component to software to associate actions/commands to each classifier output. Figure 30 below shows the functional clock diagram of the system for this trial.

Figure 30: Infrared Activated Tongue Computer Interaction System- architecture

The system was implemented as a mouse controller. The concept that the user can control the cursor and click when desired using their tongue movements proves the usability of the device for people with physical disabilities. The system is trialled by the healthy individual, the author of this research tested the functionality, Figure 31 below shows user wearing the system during the trial. The commands assigned to each classifier output are discussed in next section.

Figure 31: User wearing mask installed with sensor array

5.4 Trial Execution

The system records data for six defined tongue positions and classifies the data into six categories and then assign command to each category to accomplish tongue localization on computer screen. Five tongue movements and teeth clenching were used to generate dataset and develop six user specific tongue position parametric models. The tongue position used are defined below;

5.4.1 Neutral

The closed mouth position shown below in Figure 32 is defined as a stop command. When the user stop moving the tongue and close their mouth, that position is defined as stop command in the training data for the software.

Figure 32: Neutral position

5.4.2 Right

For activating the right command, the user is required to open their mouth slightly and touch the corner of their lips with the tip of the tongue as shown in Figure 33.

Figure 33: Right position

5.4.3 Left

For activating the left command, the user opens their mouth and uses their tongue to touch the left corner of their lips as shown in Figure 34.

Figure 34: Left position

5.4.4 Up/forward

The tip of the tongue should be touching the middle part of the upper lip as shown in Figure 35, for activating the upward/forward command.

Figure 35: Up position

5.4.5 Down/backward

The tip of the tongue should be touching the middle part of the lower lip for activating the backward/ down command as shown in Figure 36.

Figure 36: Down position

5.4.6 Click command

Teeth clenching as shown in Figure 37 was an additional movement which was captured during the collection of data. It can be used to activate commands like emergency stop, click, alarm buzzer etc.

Figure 37: Teeth clenching

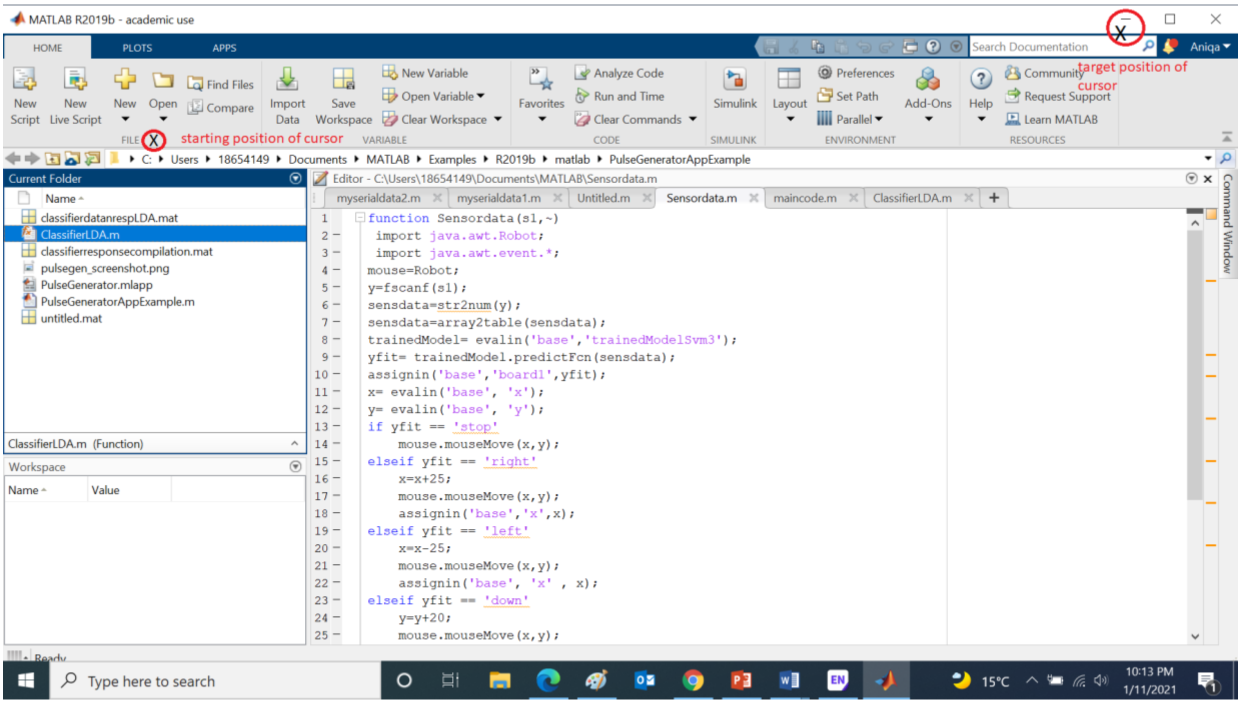
5.4.7 Cursor Control

The code attached in Appendix C Cursor control code was used to assign command to classifier output and control the cursor on the screen. The Table 7 below shows the cursor actions for each of the six systems output.

Classifier Output	**Cursor movement commended**
Neutral	Cursor stays on its current position
Right	Cursor moves to the right on screen
Left	Cursor moves to the left on screen
Up/Forward	Cursor moves up on the screen
Down/Backward	Cursor moves down on the screen
Special command	Click

Table 7: Tongue position localisation to cursor position

User was required to move the cursor from starting position shown on the left of the figure to the position shown on the right in the Figure 38 below and minimize the window using click command.



```
function Sensordata(s1,~)
 import java.awt.Robot;
 import java.awt.event.*;
mouse=Robot;
y=fscanf(s1);
sensdata=str2num(y);
sensdata=array2table(sensdata);
trainedModel= evalin('base','trainedModelSvm3');
yfit= trainedModel.predictFcn(sensdata);
assignin('base','boardl',yfit);
x= evalin('base', 'x');
y= evalin('base', 'y');
if yfit == 'stop'
    mouse.mouseMove(x,y);
elseif yfit == 'right'
    x=x+25;
    mouse.mouseMove(x,y);
    assignin('base','x',x);
elseif yfit == 'left'
    x=x-25;
    mouse.mouseMove(x,y);
    assignin('base', 'x' , x);
elseif yfit == 'down'
    y=y+20;
    mouse.mouseMove(x,y);
```

Figure 38: Starting position and target position for the experiment

The trial was conducted by one user only, the author herself. The initial plan was to test the system with 10 different users however due to social distancing restriction during COVID it was removed from the scope.

It took user 40 seconds to move cursor to the desired location on the screen and click to complete the desired action. The same task was completed in 3 seconds using the finger.

There were minor misclassifications observed during the experiment however classifier misclassification observed can be linked to the false discovery rates discussed in 4.4.4.1 Classification matrices and interpretation chapter 5.

5.5 Chapter Summary

This chapter demonstrated the potential implementation of the presented system in the area of assistive technology. It presented the test case in which the user completed a cursor movement that can be done in 3 seconds using finger. The user took 40 seconds to complete the same task. The user being able to complete the task using presented system in 40 seconds proves that Infrared Activated Tongue Computer Interaction System can be utilised by rehabilitation centres and scientists to develop tongue assistive technology.

Chapter 6

Discussion

6.1 Chapter Introduction

In this chapter the performance criteria is defined, and system performance is discussed as per the results achieved in previous sections.

6.2 Performance Criteria

The performance of a system designed to help physically disable people can be measured by following key attributes:

- Functionality
- Effectiveness
- Minimally invasive
- System range
- Ease to learn and use

The criteria is established directly from the requirements of the system defined in chapter 3 which were derived from needs of the patient. Considering the end-user of the product are physically disable people, they need a system which is minimally invasive and allows them to communicate with their environment using computer, and have the ability to operate in wider range.

6.2.1 Functionality

In order to prove the functionality of the system as tongue assistive device, it is required to show interaction with computer and activating desired commands.

Computer interaction

- Cursor movement control
- Click function

The IRTCIS has demonstrated the ability to produce six output that are then used to control the movement of the computer cursor on screen. The system has the accuracy of 95.4 % to generate desired output as discussed in detail in chapter 4.

The IRTCI system was able to generate user-defined output for each tongue position. Protostar light trap material and 3d printed black mask was used to reduce light interference, therefore reliable output signal was generated. The classification model was able to produce true positive rates of 90% and above for all six tongue positions.

Trial was carried out to evaluate system's potential to be used as assistive device. The system demonstrated cursor control and click command and was able to complete the defined task in 40 seconds as discussed in chapter 5. It proves that the system can be used to trigger alarm or call a carer in hospital or house and control things like lighting and doors in surroundings, with further development. Therefore, the developed system has the potential to be implemented as assistive technology.

6.2.2 Effectiveness

The performance of presented system can be measured by its productivity levels, the accuracy of predicting the desired output.

The system was able to accomplish positive predictive rate of 86% and above for each class/tongue position and the false discovery rate below 10% apart from one class with 14%. Overall the system demonstrated 95.4% accuracy of predicting desired output.

The system was then tested for controlling the cursor with tongue. The experiment presented in previous chapter observed that all six tongue positions were localised into cursor movement but it was relatively easier to complete the movement if it was only along one axis. The target which involved movement along x and y axis had more misclassifications which in turn increased the time to complete the movement. Same observation was noted by Head mouse: A Simple Cursor Controller based on Optical Measurement of Head Tilt[30].

We can also use Fitts's law to quantify performance.

Fitts's law is a predictive model of human movement primarily used in human-computer interaction and ergonomics. Figure 39 shows this scientific law which predicts that the time required to rapidly move to a target area is a function of the ratio between the distance to the target and the width of the target. Fitts's law is used to model the act of pointing, either by physically touching an object with a hand or finger, or virtually, by pointing to an object on a computer monitor using a pointing device[36]. According to Fitt's law, there is an inherent trade-off between accuracy and speed.

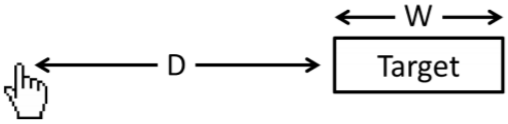


Figure 39: Fitt's law- index of difficulty

Throughput (TP) is a metric for measuring how fast the cursor is moving and is defined as:
TP = ID/MT ,
where MT is the time it takes for the user to move the cursor to the target zone and ID is index of difficulty.
Index of Difficulty (ID): ID is defined as ID = D / W ,
where D is the distance between the original location of the cursor and the centre of the target, and W is the width of the target. A higher index of difficulty means more control over the pointing device is required to navigate the cursor into the target.

Through put of the IRTCI system

The task requires the user to move the cursor into a target location. The location of the target on the screen and its size are randomly chosen,

Index of Difficulty, ID= 18.33,
Time taken to move cursor, MT= 40 s

Throughput (TP) = 18.33/40 = 0.45pixels per second.

This demonstrates that the presented system is effective and can move the cursor by 0.45 pixels in a second time, which is a promising figure to validate the technology. Throughput of 0.808 pixels per second was observed by Inductive pointing device for tongue control system for computers and assistive devices[37]. This supports that the infrared activated tongue computer interaction system can be further modified to be used in the area of assistive technology.

6.2.3 Minimally invasive

The use of Infrared technology is meant to reduce or eliminate as practicably possible the need for patient to undergo obtrusive procedures to get sensors/devices installed in their mouth. Unlike TDS, GKPTCI and other intrusive systems discussed in the literature, this research uses a minimally invasive sensing mechanism to translate tongue position into cursor movements.

This research is a step further in claiming that the minimally invasive tongue systems can be utilised for assistive technology. The sensing array is installed in front of mouth using a 3D mask. It does not require the user to go through obtrusive and expensive procedures to use the technology. It is outside of mouth so it saves the user from extra maintenance and hygiene care required by systems installed inside mouth. This is a massive step forward in tongue computer interaction using external feature space.

6.2.4 System Range

The operating range of our tongue modelling system is dependent on the user's environment. The users of our system are immobile patients. Therefore the user will either be in the bed controlling his/her environment through computer or he/she can be in a wheelchair controlling the environment or the wheel chair. Hence the user should be able to use the system in both of these scenarios.

The sensing range of IR sensor array was measured at different distances from the tongue. The Sharp IR sensor used has a sensing range of 4 to 30 cm but its optimum sensing range for our application that showed distinct variation in output voltages and was in user's comfort zone was observed to be from 4 to 10 cm.

It was established that the optimum distance between the sensor array and the mouth is 10cm. It is to ensure that the user does not have to exert too much force in extending the tongue.

The 10cm distance was decent size to be covered by a mask, so the array was inserted in a 3D mask which helped eliminate the ambient light noise that also resulted in good signal quality in the system operating range. The complete system consisted of wearable mask containing the IR sensor array and a laptop that can be easily setup in either the patient lying in bed or the patient sitting in a wheelchair. Therefore the system proved to be operatable in our user's range.

6.2.5 Easy to Use

The Infrared Activated Tongue Computer Interaction system is easy to learn. It is a user specific tongue computer interaction system, so every user can train it.

The more training data you provide in the initial setup, the better classification algorithm is achieved. Therefore for the system initial setup, the user will be required to train the system. However once you have a decent matrix of your training dataset, user should be able to use the algorithm with ease.

For further easing the process, a GUI can be developed to show the positions of tongue for each desired command on the screen. So the user does not have to remember. This is one of the future recommendations on the project.

6.3 Chapter Summary:

In Conclusion, The IRTCI system was able to meet the performance requirements and proves that the presented system is suitable for tongue computer interaction. The system was able to generate reliable output with the positive predictive rates of 86% and above for six defined tongue positions. It also demonstrated effective control of cursor with throughput of 0.45pixels per second. Although the speed of the cursor movement was relatively low and there were misclassifications observed in the real life implementation trial to control cursor, overall the system was able to demonstrate that it is reliable and can be used to control cursor with the movement of tongue. It is resilient to interference and is easy to use for the application demography.

Increasing the training data and working on future enhancements recommended in next chapter can further improve the Infrared activated tongue computer interaction system.

Chapter 7

Future Works

This project is a progressive step to design and develop minimally invasive infrared activated tongue computer interaction system. It did not develop a market –ready product. As a result, future works have been identified with the key goal to make the system ready for clinical trials.

7.1 Useful Modification

7.1.1 Mechanical design:

Mechanical design can be improved by following:

Improvising the mask- Investigate the ways to improve the fit-up of the mask so that it can appropriately sit onto the face and not get moved with user jaw movements. In current design, the mask only touches the face on nose and chin and that causes stability issues in case of big jaw movements. Changing the mask design will resolve mechanical stability issues therefore improving sensor data and it will also make it more comfortable to wear. This will make system more clinically viable.

Eliminating wired connections- Arduino mega can be replaced by Arduino Nano and can be fitted on the PCB held by the 3D mask. Bluetooth can be used to transfer data between the controller and the main computer. This will greatly improve the mechanical design with minimal effort. This will eliminate all the wires and will further reduce the system invasiveness.

Reducing physical size- The other useful modification is to investigate other infrared proximity sensor with smaller size, improved response time and less noise. This can make the system lighter and easy to wear.

7.1.2 Software design:

The software can be updated to include a user-friendly skin on the front end. The skin could be used to show the key functionalities upfront and to communicate with the user. This would make the system easier to operate. This will make system more marketable and clinically viable for training carers and users.

Future work can also include developing potential use cases for tongue assistive system and testing the presented system and models against them.

7.2 Potential Implementation:

The system has the potential to be implemented as assistive technology. With further research and clinical trials, the system can be used to help achieve independence in physically disable patients returning home. It can be integrated with a central control system capable of switching lights, generating alarm in need, opening doors and blinds. Another implementation of such system can be in rehabilitation of people suffering from dysphasia. It can be achieved by integrating the system with a game based Graphical User Interface that helps them train their tongue muscles.

Chapter 8

Conclusions

The research worked to produce a minimally invasive tongue computer interaction system. The IRTCIS design gathered reflected infrared signals using infrared distance sensors and used them to generate parametric tongue position models. A complete software system was developed that recorded the sensor outputs and trained LDA classifier using the parametric tongue position models. The classifier was able to generate desired output with the accuracy scores of 90% and above true positive rates for all six defined tongue positions. The IRTCIS was tested with real-time data, the author used the system to control computer cursor movement on screen. The user was able to complete the defined task in 40 seconds proving the potential implementation of the system in real-time application.

The system used a less invasive mechanism for sensing tongue position. It was able to utilise the change in tongue's external feature space to localise tongue position. Infrared distance sensor array was used to sense the tongue movement outside of the mouth, making the system minimally invasive. Parametric tongue position models for six positions were developed to train classifier. Software system was trained to classify device output into six categories based on the training data and localise tongue position into six defined cursor controls. The presented system used novel approach to localise tongue position. This research is a meaningful step towards using minimally invasive infrared activated tongue computer interaction in assistive technology.

The research was split into following major phases;

- Detailed investigation into the existing tongue computer interface systems
- Design and development of sensing unit comprising of infrared sensor array
- Parametric tongue position models
- Classifier Training and validating its results
- Real-time testing of the system

The research designed and developed a less invasive mechanism to sense tongue movement. It used Sharp GP2Y0A41SK0F distance measuring sensor to sense tongue motion. The sensor was selected because it output is not influenced by the variety of the reflectivity of the object and the environmental temperature. The other advantage was that it consisted of IRLED, position sensitive detector and signal processing circuitry all in one small unit. 2 x 3 rectangular array configuration was used to keep it similar to computer screen aspect ratio. Protostar light trap sheet was installed on sensor to reduce light noise caused by diffused light in the environment and crossover talk between sensors. Experiments discussed in chapter 4 show the improvement in the output signal with the protostar, it generates repeatable reliable signal. A 3d black mask was used to wear the sensing array in front of nose and mouth and block ambient light present in system's environment. The design and development of sensing unit followed an iterative process to achieve good quality, reliable output signal array for each tongue position.

Parametric tongue position models were generated using the developed sensing unit for six different positions. These were user-specific models. The author used the wearable sensing unit to record output of sensing unit in an array. Tongue position used to generate parametric tongue models are right, left, up, down, neutral/ (no movement closed mouth), and teeth clenching. Appendix B Parametric Tongue Position Models-
Training dataset for classifier shows the generated tongue position models.

Parametric tongue position models are then used as a training dataset to develop machine learning algorithm. As our training data can be categorised into separate classes we will train classifier. The classifier will use the known input data and known output data to train an algorithm to predict output response for future input values. LDA classifier is used to suit our linear system. It divides feature space into linearly arranged clusters. Our trained classifier was able to achieve overall accuracy score 0f 95.4 %. Refer to 4.4.4.1 Classification matrices and interpretation for detailed discussion on classifier performance.

Finally the research presented a real-time implementation of the system to prove the potential implementation in the area of assistive technology. The author used the system to localise six tongue position into six usable commands. The commands defined to control cursor are defined in Table 7: Tongue position localisation to cursor position. The user was able to move the cursor on screen with the tongue movement and perform a click function.

The defined task to move the cursor and minimising a window was completed in 40 seconds. Throughput was calculated to be 0.45 pixels per second using Fitts law. It showed that the user can effectively move the cursor on screen and perform the clicking operation. Therefore, the system can potentially be used to control an alarm or call for help using computer cursor movements after further development. Thus it has the potential to be implemented in assistive technology.

In Summary, the Infrared Activated Tongue Computer Interaction System (IRTCIS) developed at Curtin University used a less invasive mechanism for sensing tongue position. It was able to utilise the change in tongue’s external feature space to localise tongue position. Software system was trained to classify device output into six categories based on the training data and localise tongue position into six defined cursor controls. This research is a meaningful step towards using minimally invasive infrared based tongue computer interaction in assistive technology.

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Appendices

1. Appendix A Arduino code for capturing IR sensor output

```
int i=0; int j=0; int k=0;
int sens[6] = {A0, A1, A2, A3, A4, A5};
int output[6]={0};
int toutput[6]={0};
int avgsen[6]={0};
int readings= 20;
void setup() {
  // put your setup code here, to run once:
Serial.begin(9600);
}
void loop() {
  // put your main code here, to run repeatedly:
for (j=0; j< 6; j++){
  for (k=0; k<readings; k++){
    output[j]=analogRead(sens[j]);
    toutput[j]= toutput[j] + output[j];
  }
  avgsen[j]= toutput[j]/readings;
  toutput[j]=0;
}
for(j=0; j<6; j++){
  Serial.print(avgsen[j]);
  Serial.print("\t");
 }
 Serial.println();
 delay(500);
}
```

2. Appendix B Parametric Tongue Position Models- Training dataset for classifier

Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Response
814	779	671	814	818	772	'right'
818	781	659	810	839	776	'right'
810	765	682	824	848	763	'right'
818	784	662	811	865	781	'right'
813	795	679	817	840	767	'right'
810	794	678	818	865	765	'right'
797	776	671	821	883	778	'right'
825	796	670	809	809	773	'right'
814	766	686	818	851	767	'right'
804	779	679	820	870	769	'right'
819	779	668	809	833	785	'right'
815	786	690	816	856	756	'right'
801	778	678	823	872	772	'right'
810	776	675	817	869	780	'right'
816	791	679	811	863	765	'right'
802	779	679	830	870	757	'right'
816	770	649	812	874	777	'right'
823	783	650	811	849	771	'right'
809	793	690	829	864	706	'right'
798	770	673	829	848	781	'right'
819	769	674	809	848	780	'right'
811	791	684	814	861	728	'right'
810	783	672	813	869	777	'right'
818	795	680	806	855	761	'right'
810	803	685	818	828	743	'right'
790	714	685	841	880	766	'right'
816	774	669	807	853	773	'right'
822	793	668	810	824	774	'right'
821	802	683	813	848	756	'right'
809	782	672	819	873	774	'right'
817	803	692	816	851	704	'right'
802	708	685	827	877	782	'right'
801	774	676	818	879	785	'right'
831	750	660	797	836	757	'right'
831	750	660	797	836	757	'right'
816	796	703	815	756	716	'right'

810	793	685	820	864	767	'right'
802	775	688	821	864	774	'right'
816	777	678	812	818	716	'right'
798	792	695	830	888	784	'right'
752	834	727	809	843	768	'left'
740	802	716	826	748	785	'left'
766	839	696	798	849	771	'left'
738	818	729	833	851	774	'left'
751	821	724	825	775	773	'left'
760	816	711	809	846	793	'left'
756	838	743	823	837	759	'left'
752	803	720	821	873	786	'left'
767	815	729	809	867	769	'left'
773	838	729	806	851	764	'left'
744	813	746	838	859	768	'left'
757	810	724	806	821	783	'left'
756	816	731	816	845	779	'left'
760	828	716	817	858	771	'left'
755	808	718	817	825	793	'left'
761	844	733	810	847	765	'left'
747	828	740	833	842	769	'left'
741	799	736	831	886	777	'left'
765	812	706	809	847	787	'left'
774	789	722	814	836	763	'left'
753	820	730	819	847	773	'left'
761	816	727	816	840	779	'left'
763	825	724	817	845	763	'left'
741	803	677	832	859	780	'left'
756	805	710	805	864	790	'left'
756	805	710	805	864	790	'left'
772	819	717	801	830	775	'left'
758	789	738	819	839	761	'left'
742	823	730	831	850	770	'left'
756	816	718	820	846	781	'left'
750	811	727	831	844	772	'left'
758	797	715	816	860	786	'left'
772	828	709	810	814	778	'left'
777	777	670	806	829	757	'left'
735	821	673	846	856	761	'left'
758	809	712	821	849	786	'left'
759	816	717	809	857	775	'left'
758	833	723	817	841	771	'left'
766	812	711	809	855	791	'left'
760	787	736	804	802	755	'left'
758	787	644	812	844	766	'up'

764	821	651	818	820	748	'up'
764	821	651	818	820	748	'up'
764	811	644	820	844	761	'up'
765	790	607	831	840	759	'up'
775	807	646	809	829	766	'up'
762	776	647	830	843	766	'up'
782	814	645	801	831	768	'up'
772	815	648	826	840	758	'up'
781	825	661	813	832	753	'up'
762	797	659	835	857	767	'up'
780	814	670	815	846	756	'up'
770	762	650	816	745	772	'up'
769	827	664	819	834	753	'up'
777	816	587	811	836	761	'up'
759	839	664	839	825	745	'up'
766	810	649	827	846	771	'up'
764	800	652	834	861	718	'up'
792	776	645	805	827	773	'up'
774	788	656	828	839	763	'up'
788	824	664	817	823	747	'up'
763	806	655	836	849	727	'up'
777	785	673	828	724	755	'up'
769	796	646	817	866	776	'up'
786	794	611	811	831	732	'up'
785	787	651	805	830	756	'up'
761	831	665	831	840	748	'up'
772	813	649	815	850	762	'up'
758	780	654	838	847	771	'up'
782	811	648	809	788	775	'up'
775	809	646	818	846	735	'up'
799	809	663	800	821	761	'up'
769	813	673	824	839	756	'up'
761	813	647	822	850	748	'up'
771	779	647	815	855	773	'up'
772	791	659	820	844	754	'up'
768	815	648	811	833	771	'up'
769	818	667	824	832	699	'up'
769	818	667	824	832	699	'up'
775	825	668	820	836	751	'up'
726	787	682	833	789	770	'down'
744	807	659	814	833	791	'down'
736	808	683	831	871	769	'down'
736	797	634	826	857	768	'down'
739	792	665	832	868	792	'down'
746	816	667	810	861	780	'down'
734	761	666	815	870	777	'down'

730	802	676	830	820	763	'down'
732	810	666	820	869	779	'down'
721	802	679	839	867	767	'down'
730	802	661	826	796	792	'down'
729	803	664	822	876	788	'down'
751	794	663	807	846	780	'down'
729	782	632	832	865	768	'down'
730	820	653	831	858	776	'down'
726	795	675	831	860	783	'down'
729	790	669	826	868	773	'down'
737	768	663	814	822	795	'down'
761	823	672	811	859	767	'down'
756	774	670	828	853	773	'down'
737	813	683	840	855	765	'down'
743	802	660	830	873	784	'down'
751	807	665	828	867	783	'down'
742	783	656	818	860	787	'down'
742	783	656	818	860	787	'down'
757	815	665	820	833	782	'down'
758	777	678	824	854	768	'down'
743	788	682	830	873	768	'down'
744	801	672	827	883	782	'down'
753	810	667	816	869	786	'down'
741	796	669	815	865	772	'down'
749	823	674	825	861	770	'down'
753	785	669	822	847	770	'down'
741	799	674	836	863	774	'down'
749	802	670	827	871	783	'down'
745	815	656	831	848	786	'down'
771	813	671	816	831	777	'down'
750	812	677	827	872	775	'down'
753	784	675	828	858	778	'down'
751	812	671	823	835	782	'down'
776	825	668	808	834	784	'stop'
792	849	679	797	855	769	'stop'
768	832	681	820	881	776	'stop'
773	842	685	814	776	768	'stop'
773	842	685	814	776	768	'stop'
771	773	665	816	890	794	'stop'
778	832	667	808	876	778	'stop'
787	825	662	794	774	793	'stop'
783	829	680	812	861	764	'stop'
778	842	681	809	871	768	'stop'
761	821	681	833	825	778	'stop'
778	825	669	805	877	784	'stop'
778	821	665	807	887	781	'stop'

787	850	675	803	832	773	'stop'
782	783	678	809	873	772	'stop'
769	840	685	821	868	759	'stop'
768	817	668	823	883	783	'stop'
777	825	673	809	889	778	'stop'
789	833	664	804	867	781	'stop'
785	842	612	813	865	776	'stop'
783	821	604	813	866	773	'stop'
774	834	662	825	876	776	'stop'
775	784	675	815	878	778	'stop'
782	822	667	811	869	787	'stop'
785	831	677	802	871	779	'stop'
786	840	675	815	860	775	'stop'
778	830	682	811	870	776	'stop'
773	833	676	819	876	772	'stop'
783	818	672	805	885	761	'stop'
779	816	674	814	878	777	'stop'
785	837	673	802	876	775	'stop'
769	830	673	821	875	733	'stop'
781	838	674	809	863	777	'stop'
778	824	654	818	882	778	'stop'
782	839	660	807	869	758	'stop'
779	823	669	820	880	782	'stop'
783	835	681	810	791	764	'stop'
782	825	663	808	876	790	'stop'
781	833	680	809	868	767	'stop'
793	832	670	801	829	771	'stop'
743	723	676	772	828	732	'click'
721	724	668	790	765	740	'click'
735	743	678	773	821	732	'click'
735	732	667	779	836	761	'click'
732	690	695	790	814	716	'click'
710	717	658	804	843	712	'click'
722	722	568	790	851	741	'click'
735	660	651	777	853	771	'click'
735	660	651	777	853	771	'click'
736	724	682	780	830	729	'click'
730	723	666	784	848	716	'click'
735	743	682	779	830	734	'click'
737	680	679	782	831	727	'click'
719	743	698	801	832	719	'click'
711	712	671	795	863	713	'click'
732	729	649	778	845	741	'click'
737	722	588	774	831	743	'click'
732	739	693	783	836	724	'click'
731	728	674	778	841	709	'click'

741	741	691	766	810	728	'click'
721	744	679	791	833	754	'click'
713	706	687	794	858	707	'click'
730	722	658	784	849	759	'click'
741	732	608	776	810	760	'click'
731	741	677	773	825	732	'click'
722	712	679	792	837	702	'click'
729	731	670	780	841	757	'click'
730	738	680	787	826	756	'click'
720	714	688	786	841	750	'click'
720	715	679	785	854	706	'click'
732	731	667	777	844	764	'click'
731	742	625	781	835	752	'click'
723	733	688	789	838	741	'click'
728	723	674	786	842	718	'click'
732	735	672	776	843	755	'click'
730	732	686	778	837	747	'click'
716	730	679	796	828	725	'click'
731	725	672	778	846	719	'click'
721	735	676	783	841	758	'click'
735	729	681	786	843	751	'click'

3. Appendix C Cursor control code

```
function Sensordata(s1,~)
 import java.awt.Robot;
 import java.awt.event.*;
mouse=Robot;
y=fscanf(s1);
sensdata=str2num(y);
sensdata=array2table(sensdata);
trainedModel= evalin('base','trainedModelSvm3');
yfit= trainedModel.predictFcn(sensdata);
assignin('base','board1',yfit);
x= evalin('base', 'x');
y= evalin('base', 'y');
if yfit == 'stop'
   mouse.mouseMove(x,y);
elseif yfit == 'right'
   x=x+25;
   mouse.mouseMove(x,y);
   assignin('base','x',x);
elseif yfit == 'left'
   x=x-25;
   mouse.mouseMove(x,y);
   assignin('base', 'x' , x);
elseif yfit == 'down'
   y=y+20;
   mouse.mouseMove(x,y);
   assignin('base', 'y', y);
elseif yfit == 'up'
   y=y-20;
   mouse.mouseMove(x,y);
   assignin('base', 'y', y);
elseif yfit == 'click'
   mouse.mousePress(InputEvent.BUTTON1_MASK);
   mouse.mouseRelease(InputEvent.BUTTON1_MASK);
end
end
```