Development of a Wearable Exoskeleton for Arm Rehabilitation

By

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17868

Dissertation submitted in partial fulfilment of the
requirements for the
Bachelor of Engineering (Hons) (Electrical
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CERTIFICATION OF APPROVAL

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AND ELECTRONICS ENGINEERING)

Approved by,

____

(Ir. Dr. Perumal A/L Nallagownden)

UNIVERSITI TEKNOLOGI PETRONAS
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May 2015

STATEMENT OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my

own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Momen Kamal Tageldeen MohammedOsman

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All praise and hamdu to Allah,

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ABSTRACT

With the increasing population of aging and disabled individuals, the need for a more effective and efficient solutions is at peak, Powered Exoskeletons are wearable robots that can be attached to the disabled limb with the goal of adding power to, or rectifying the limb functionality , one of its application is rehabilitation. This study review relevant research, technologies and products, while critically analyzing them and addressing some of the current problem faced by the researchers in this field, such as the use EMG signal as a primary input to the controller. This research propose an adaptive EMG-based upper limb exoskeleton that is built on a fuzzy controller. The paper strives to propose a wearable general-user Exoskeleton, Built around an interactive gaming interface to engage the patients in the rehabilitation process. The games and exoskeleton assistance degree can be preset – on medical supervision – to different training patterns. Ultimately, the project strives to afford normal daily life for those who needs it.

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Chapter 1:

1. Introduction

1.1 Background

The number of elderly citizens and aging workforce is expected to increase dramatically- Figure(1.1) -, that to the addition of individuals with physical disability, genetic disorders -both full & partial - and injuries due to sport, accidents, traumas and strokes . Stroke is a pressing global issue ranked as the second or third cause of death in many countries, in the U.S. each year, approximately 795,000 Americans suffer a stroke per years, about 600,000 of these are first attacks, and 185,000 are recurrent attacks. Almost 80% of those who have had strokes before will suffer from some degree of motor disabilities. Producing a standing population of people with decayed motor functionalities [1] [2] [3] [4] [5] [6] [7]. Strokes damages the brain and deleteriously affect the movement and gait of the patients, however the brain is able to reorganize through rehabilitation.

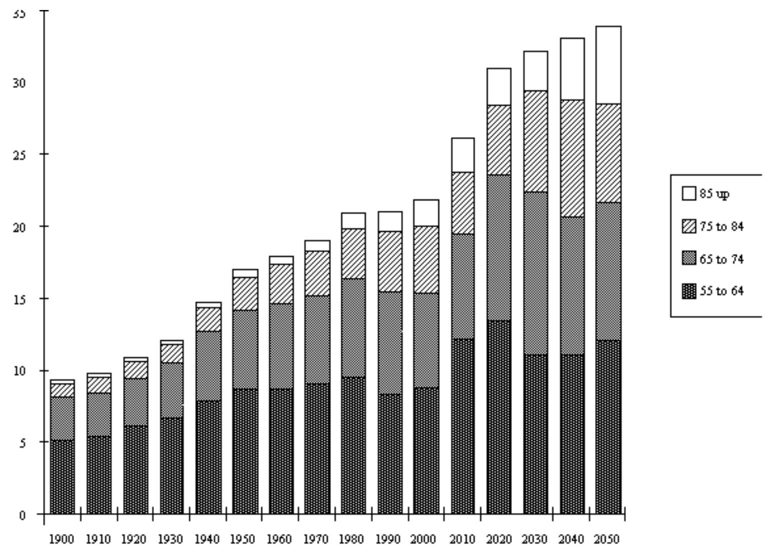


Figure 1-1: Aging population projection in US expressed in millions [8]

In the Malaysian context, Stroke is the second cause of death among heart diseases and HIV, with 11,943 deaths amounting for 11.67% deaths as shown in Figure (1.2). Approximately 1,400,000 Malaysians are 65 years old and above, presenting more than 5% of the demographics of the country [8].

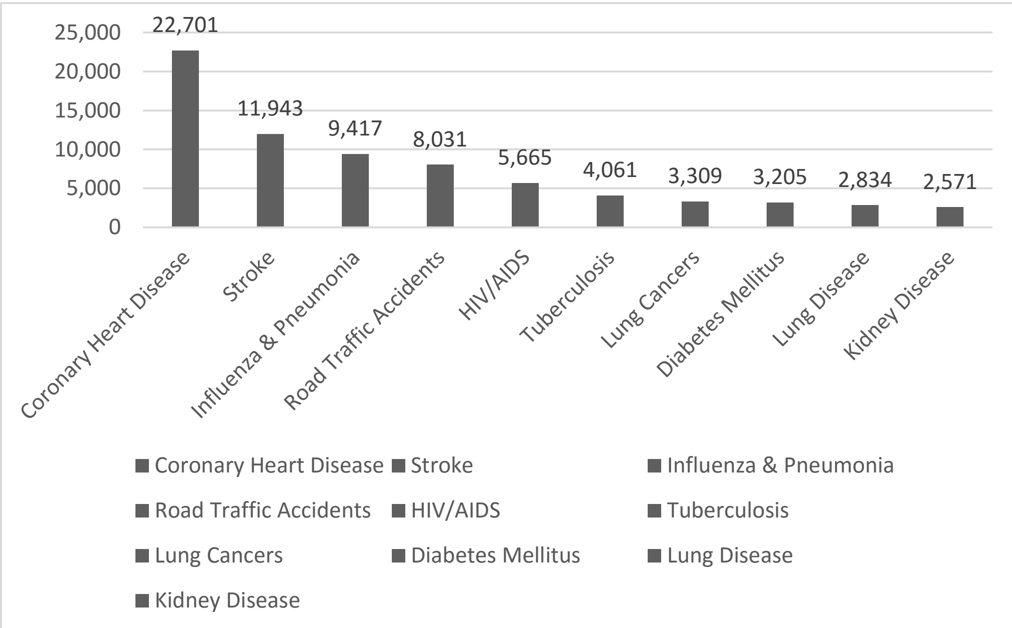


Figure 1-2: Top ten causes of deaths in Malaysia [9]

The current state of Rehabilitation is both inefficient in terms of wasted therapists time and patients' session and ineffective because there is no guarantee that the patient is exerting enough force and attention in the practice. Today's technology had made the solution within grasp, with the current miniature motors that are capable of providing high torque like those of Maxon and Faulbaul, with addition to the emerging field of machine learning, it is possible to develop a portable, smart robot that are able to assist patents in their daily life activities and are able to learn their moving patterns ensuring smooth response and comfortable use; eliminating certain degrees of disability, and helping in patients rehabilitation and ultimately recuperation.

1.2 Problem Statement

This project aims to address the following problems faced by researchers and developers of Exoskeletons:

1- The imprecision and situation-dependency inherited with the use EMG signals to measure activation electrical potential generated in muscles cells.
2- The ineffectiveness of rehabilitation using fully assistive robots, due to the concern that the patient can depend on the robot without exerting any effort, which results in slackness.
3- The complexity of modeling the upper human upper limb as a function of EMG electrodes signals, which complicates controller design.
4- The high cost and importability of current clinical Exoskeletons, which render them inapt to help patients with permanent or long-termed injuries in their daily life activities and limit their applications.

1.3 Objectives

The Objectives can be summarized in:

1- To review and chose an algorithm/mechanism to enhance EMG signals as input.
2- To ensure that the patient is exerting enough effort in the system.
3- To produce a reliable model for the Exoskeleton system.
4- To design a cheap, light-weight wearable exoskeleton to help patients in their daily activities.

1.4 Scope of study

The expected outcome of this study is to develop an upper-limb (elbow flexion/extension) wearable robot that provides assistive force for the use in rehabilitation and to help patients with their daily activities, such as pushing their bodies up and lifting object. The power assist exoskeleton proposed in this study is controlled by EMG signals from the muscles. The study seeks to identify an EMG signal processing technique that reflects the intention of the user in terms of direction and strength. The study will propose a mathematical model for the controller using techniques such fuzzy logic in order to ensure a smooth control system that provides functionality and maximum conformity with the user arm movement. This study also investigates and suggests a novel mechanism and peripheral sensory system to map the user coordinates in 3D space, allowing the data acquisition for medical purpose and developing games to increase patient engagement and rehabilitation quality

The Exoskeleton will use the EMG signal from electrodes attached to the subject muscles as input to the system that decides the level of assistance needed (from 0-100 %) to ensure that the patient will exert enough efforts despite of his disability degree. The mechanism and algorithms are to be extended later to include *glenohumeral joint* (flexion/extension, adduction/abduction, medial rotation/lateral rotation).

1.5 Chapters Outline

The following chapter – literature review- will expand on Exoskeletons, theirs state of art and the main subsystems that will be developed throughout the robot, A detailed review of previous works and critical analysis are also presented in chapter 2.

Chapter 3, describes the methodology taken to gather data and develop the subsystems introduced in chapter 2. Chapter 3 explains with details the step taken to realize the project with critical and analysis and expansion on the principles acting as fulcrums to the methods used. Finally the chapter presents the sensors used and reasoning behind the selections.

Chapter 4, presents the results of the project including fabrication of hardware and algorithms developed, it also includes simulation results from where it was necessary to carry out simulations before implementations.

Chapter 5, is the last chapter concluding the study and presenting recommendations for future work, the chapter digress to show the societal benefits and impacts the product can achieve.

Chapter 2:

2. Literature Review

2.2 Exoskeleton

An exoskeleton is derived from Greek world “exo” which means outer and the world “skeletos” which means skeleton. An Exoskeleton is an external rigid structure that supports and protects an animal’s body, which is found is bugs abundantly. Powered exoskeletons (hereafter referred as robotic exoskeletons or just exoskeletons) are wearable robotics structures that somewhat mimic the musculature of the humans, they attached to subject’s limbs, in order to replace or enhance their movements. They complement the movement of the human limb and provides it with supportive force [9]. The history of Exoskeleton can be traced to 1988, where the idea of motor aided rehabilitation was proposed by Khalili and Zomlefer [10]. And since that a lot work has been carried out in the field

The function of medical-purpose exoskeletons is to assist patients in moving their limbs in the rehabilitation and ensure they are exerting enough effort in the process. The exoskeleton should be of an intelligence so it’s apt to replace the nurses or the clinical staff in doing the job of assisting and coordinate the patient exercises; since it impossible for a human staff to maintain the same quality and pace of exercises insuring the optimal recovery. [11] Something that robots can do more effectively and efficiently. Robots used to address those problems can be categorized based on their functionality to: 1) Posture support 2) rehabilitation 3) assistance or body parts replicas.

The idea of motor aided therapy was earlier introduced by Khalili and Zomlefer in 1988 [10] .A number of research have been carried in this field to produce exoskeletons that accomplished their goals, although a lot of them are bulky sized and used for clinical purposes, one example of an upper-limb exoskeleton is MIT-MANUS, developed by researchers from Massachusetts Institute of Technology, MIME (Mirror Image Motion Enabler), developed by the joint group from VA Palo Alto R&D Research Center and Stanford University [12]. In 2001 HAL (hybrid assistive leg) a lower-limp predictive control robot have been developed by the University of Tsukuba, Japan [13]. Other Exoskeletons have been developed, but it is yet to develop a general user exoskeleton that is portable and cheap and can be commercialized an made available for those patients who need it, That is due to the complexity of modeling the human body and difficulty of extracting clean, reliable signal form muscles that accurately indicates activities and forces developed in the muscles. This study propose a novel wearable EMG-based upper-limb exoskeleton that is built on fuzzy logic.

Researches have argued that exoskeletons can have a negative impact on the patient physical state in the rehabilitation process leading to deteriorated motor functions; the reason is that subject may relay on the exoskeleton to provide the force needed for the activity undergone, this lack of effort will lead to the “slackness” of the subject muscles. [14] Patients with long term injuries are expected to be using the Exoskeleton for an extend time; which requires the Exoskeleton to be light weighted and wearable, whereas most Exoskeletons available nowadays are bulky and stationary for clinical usage and under a specialist supervision

The following figure (2.1) presents the main layout of the Exoskeleton divided into two main sections: Mechanical subsystem and Electronics subsystem including the algorithm. The study will follow the dichotomy until Chapter 4 where the two systems will are reconciled to present the final result. The study is oriented to the Electronics subsystem.

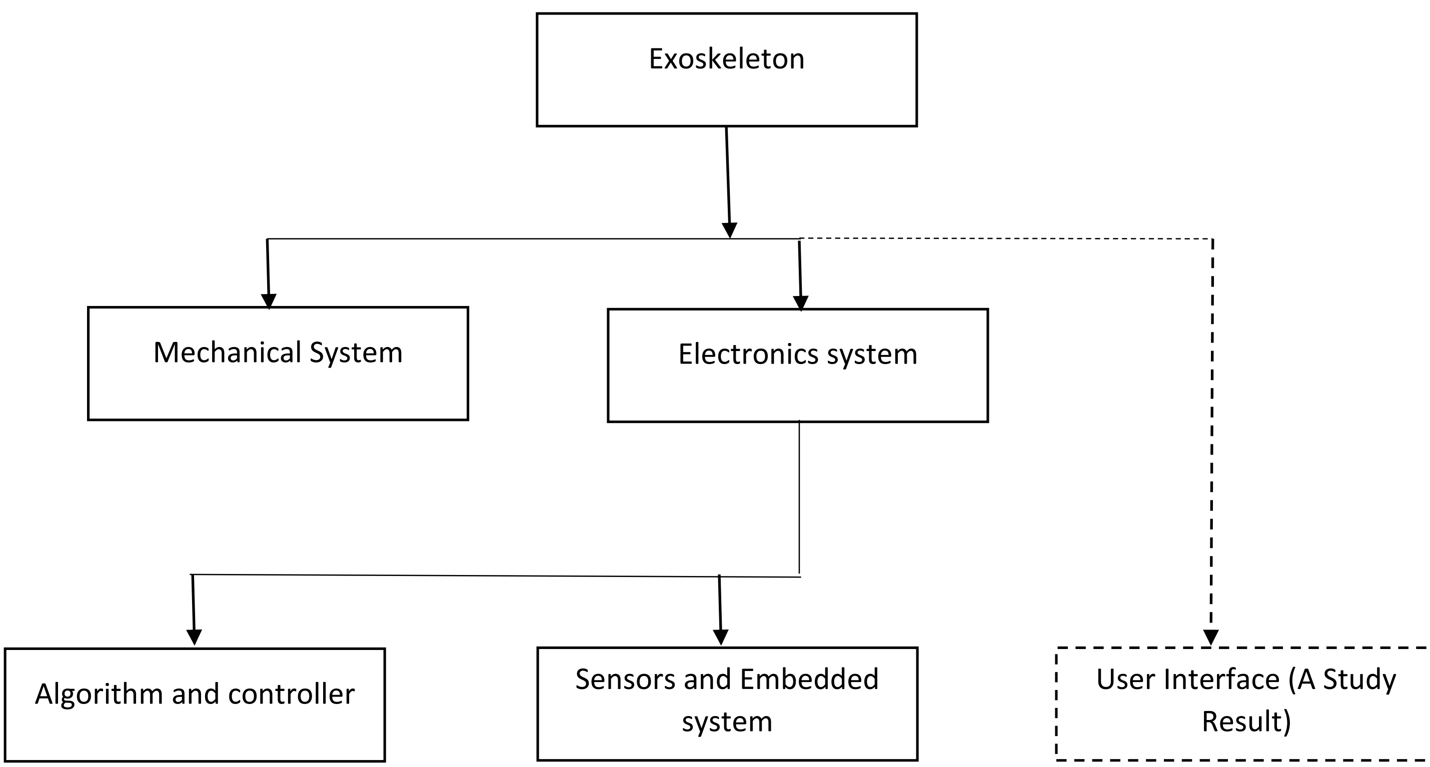


Figure 2-1: Exoskeleton Main subsystems

2.3 Mechanical Designs of Exoskeletons

2.3.1 Related Work

Table (2-1) summaries the previous research and work done on rehabilitation robots and Exoskeletons with a focus on the mechanical designs and specifications of the systems.

Table 2-1: Previous work in Exoskeletons with a focus on the mechanical design

Exoskeleton	Developer	Year	Mechanical structure type	Degrees of freedom	Main input
MIT-MANUS [15]	Developed by MIT	1990	Upper limb End affecter Stationary	2 degrees of freedom	EMG - driven
HAL (Hybrid Assistive Limb) [13]	University of Tsukuba, Japan	2001	Lower limb Wearable	one DOF in the sagittal plane	Pattern recognition Fixed number of patterns
ARMin [16]	Swiss Federal Institute of Technical in Zurich with collaboration therapists and physicians from University Hospital Bulgiest, Zurich	2003 - 2006	Upper limb Bulky Stationed	6 degrees of freedom	Automated pattern and not driven by the users EMG signals
LOKOMAT [17]	HOCOMA Inc	2004	Lower limb Bulky stationed	1 degree of freedom	Automate the gait training with embedded system of Body-weight Supported Treadmill Training

2.3.2 Critical Analysis

With reference to Table 2-1, we can argue that the merits of MIN-MANUS is that it's EMG driven, which suggests that, for the user to actuate the system he must exert enough effort in his muscles. This is really important because it means that the patient will not fully-depend on the robot and slack in the training session. On the other hand the robot supports only two degrees of freedom and it's not wearable, but rather stationed.

An interesting Exoskeleton is HAL (Hybrid Assistive Limb), the great merit of this Exoskeleton is that it's wearable and can actively assists patients in their daily life, However the Exoskeleton provides fixed movement patterns using a phase recognition algorithm, the Exoskeleton was developed mainly for gait and the lower limb.

ARMin is an upper limb Exoskeleton providing a great deal of mobility since it provides 6 degrees of freedom, the Exoskeleton is built around a rehabilitation interface. The Exoskeleton is huge and bulky and isn't designed to be used in daily life activities. Lastly LOKOMAT is also bulky and huge, it's mainly designed for rehabilitation and for gait patterns corrections.

The Exoskeleton in this paper provides some of the merits explained here, in terms that it's EMG driven and it only estimates the torque and doesn't set limitations on the patterns of movement – which is more applicable to be implemented on an upper limb that on a lower limb exoskeleton- the exoskeleton is wearable to assist patients in there mundane activities. It's also built around a rehabilitation interactive system to ensure quality of the training. The first prototype – discussed in this paper scope- provides one degree of freedom and it powers the elbow joint movement.

Figure 2-3: MIN-MANUS [15]

Figure 2-2: LOKOMAT [27]

Figure 2-4: Hybrid Assistive Limb (HAL) [13]

2.4 Electronics System

The presentation of this system is limited in this chapter to two subsection: EMG signals and Controller Algorithm.

2.4.1. EMG signal Analysis

Human's muscles generate electrical activities when they contract- which seems more prevailed in the eel fish, where it generate sparks of electricity from its muscles tissue contraction.The electro-diagnostic medicine technique for evaluating and recording the electrical activity produced by skeletal muscles is referred to as Electromyography. While a lot of research challenged the degree of control that EMG signals can provide to the system, arguing they are noisy , situation and user dependent (on the same muscle the signal features change if the position of the electrode is changed). The EMG is of a noisy nature and is dependent on the situation and neurochemical mental statue of the subject; which requires a sophisticated signal analysis and enhancement perhaps using Artificial Intelligence optimization Techniques. [11]

Studies have argued that the subject or patient will be able to adapt his EMG profile to meet his requirement of movement [14], this conclusion is definitely not enough to stand on as a fulcrum for the design of a supposed highly delegate and sensitive rehabilitation tool. A lot of algorithms seemed to have overcome this difficulties and meritorious result are out there, like the MIT-MANUS [12] .it appears that the control algorithm used in the robot determines to a far extent its reliability and functionality. [11]

The EMG signals are used in this project are the primary mean for driving the exoskeleton. The EMG signals are noisy and highly dependable on the condition and the state of the subject, a pre-processing is needed to enhance the signals, below are two sampling technique proposed by different research in the field:

1) EMG signals were sampled with a rate of I kHz using electrodes placed on the subject 2 cm apart along the longitudinal axis of the muscle belly, specifically using Ag/AgCl 8 mm diameter bipolar surface electrodes by Prissonse&Co. in Milano, Italy. The signals are then processed by Appling a band pass filter with cut off frequencies at 10 and 500 Hz, the data are then amplified to 2000 multiplication. The EMG data are harmonic signal, the linear envelope was then extricate to exhibit the signal features [14]

2) This sampling techniques focuses on features extraction from RMS values; the EMG data are sampled at are a rate of 2 kHz, and each 100 samples are bundled and RMS value is calculated for the 100 samples at 500μsec.

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2} \qquad (2.1)$$

Where vi is the samples and N are the number of samples, 100 is this case. Thus an RMS value is calculated each 5msec. [5]

2.4.2 Related Work of Controllers and Algorithms

Table (2-2) shows a list of related systems, the project research focused on pin pointing the most noticeable contribution in the field of medical Exoskeletons, the figure exhibits a brief summary of the related papers with their merits and demerits.

Table 2-2: Related Work on Exoskeletons Algorithms and controllers

Author	Title	Year	Method	Merit	Demerit
Y. Sankai and K.Kasaoka [13]	"Pedictive Control Estimating Operator's Intention for Stepping-up Motion by Exo-Skeleton Type Power Assist System HAL,"	2001	Phase sequence	Wearable Full-body	-Clinical use only -Limited phases and motion patterns
K. Kiguchi, M. H. Rahman and M. Sasaki [18]	"Neuro-Fuzzy based Motion Control of a Robotic Exoskeleton: Considering End-effector Force Vectors"	2006	Neuro-fuzzy controllers	Usage of an end effector	-Attached to wheelchair -Reduced portability and application
Tommaso Lenzi ,Stefano Marco Maria De Rossi, Nicola Vitiello, and Maria Chiara Carrozza [14]	Intention-Based EMG Control for Powered Exoskeletons	2012	Proportional EMG controller	The results of the ability of humans to adapt with the exoskeleton	The subject needs to adapt Stationary
Shahid Hussain, Sheng Q. Xie and Prashant K. Jamwal [19]	"Adaptive Impedance Control of a Robotic Orthosis for Gait Rehabilitation"	2013	Adaptive Impedance control	Use of human-robot interaction as input	Stationary settings

2.4.3 Critical Analysis

In this research the pervious related works have been studied, the most noticeable and related works are summarized in Table (2-2), in 2006 a research by K. Kiguchi, M. H. Rahman and M. Sasaki, has developed a neuro-fuzzy controller for a wheelchair based upper-limb, the study attested to the noisy and perhaps ostensible nature of the EMG signal. To overcome this; the study proposed the use of an end effector, which is a strain sensor to measure the angle between the wrist and fore arm. This is based on the assumption that the hand and fore arm in normal condition have approximately 180 degrees between them. The greatest demerits of the Exoskeleton that is wheel chair mounted; which limits it applications and portability. [5]

Another important study was carried in 2013 by Shahid Hussain, Sheng Q. Xie and Prashant K. Jamwal, although it shares the same demerits of the previous study: being stationary and for clinical use only this Exoskeleton is not based on EMG signals at all, but rather it uses force and strain sensors to measure the interaction between the suit and the subject, the controller measures the values and strives to keep them close to the set values, by moving actuators and thus reducing or increasing the pressure/force. [19]In 2012 a study by Tommaso Lenzi ,Stefano Marco Maria De Rossi, Nicola Vitiello, and Maria Chiara Carrozza has reached a promising conclusion, the study developed an EMG-based upper limb Exoskeleton, the study carried experiments on a number of subjects and reach a conclusion that the EMG inaccuracy may not propose any serious issue since the subjects were able to adapt to the Exoskeleton and had better control over it through time [14] the system was stationary.

HAL "hybrid Assistive Limb" was develop in japan in 2002 by Y. Sankai and K.Kasaoka as a lower limb Exoskeleton that uses EMG signal to predict the user's next motion phase among a limited number of phases, currently HAL is a full body Exoskeleton and is used in some clinics in Japan [13]. It can be concluded that regarding the controversial EMG nature, it seems that accurate features can be extracted from them by using appropriate analysis techniques.

In this study, an upper limb EMG-based Exoskeleton is proposed, with an impedance control scheme that senses force difference developed between the Exoskeleton and patient arm.

Chapter 3:

3. Methodology

3.1 Research Methodology

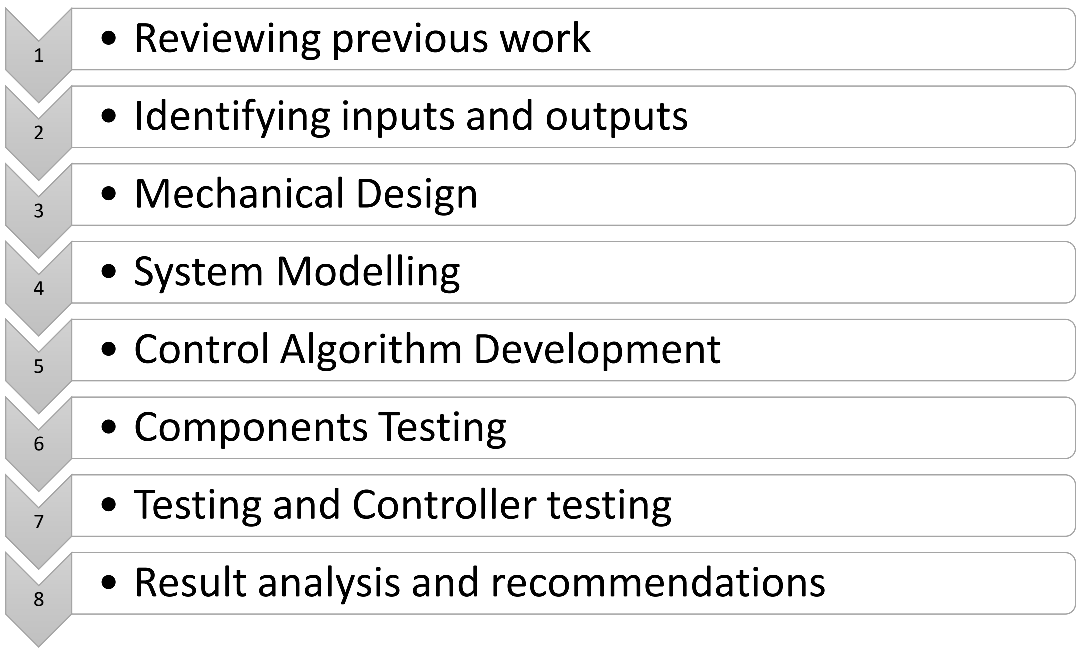


Figure 3-1: Research Methodology

The research methodology – As shown in figure (3.1) has been divided into 8 steps, the tasks are to be carried out orderly to achieve meritorious results within the time and budget constraints. The first step was to carry extensive literature review on the topic and existing Exoskeleton technologies. Critical analysis has been developed to identify the merits and demerits of similar systems in order to ensure novelty and impactful results.

The second steps is the basic of developing the control system of the Exoskeleton. The input and output have been chosen from a continuum of physical variables. The input was chosen to be the EMG signals developed in the muscles, which reflects the force developed in the respective muscles, reservation were taken on that the EMG signals are noisy and they depend on the subject and testing conditions, those reservations are to be ameliorated by means of AI techniques. The system output is force supplied by an actuators that is proportional to the force developed in the subject's muscles.

The third step is designing the mechanical structure of Exoskeleton, it was taken into account the need for a light weighted and portable design, the structure is aimed to be used by patients for extended periods thus stressing attention to ergonomics. This step includes the decision on the sensors required for sensing the input parameters the fourth step is to model the bio-mechanical process and the physical interaction with the structure.

The fifth step is the fulcrum and main focus of this research, a great time is invested in this step, the algorithm is partially compromised of fuzzy logic to allow the Exoskeleton to deal with uncertainty and different patients to ensure sustainable product with optimum performance.

The sixth steps is components testing and interfacing, which includes all the sensors employed in the system and the controller responsible for controlling the operation of the system, the components are to be tested and tuned to ensure that physical parameters are sensed reliably.

The seventh step is to validate the controller theory by testing it on patients and subjects, the controller will be taught patterns and its behavior will be closely monitored, this steps will also include tuning the controller's parameter to enhance its effectiveness and to achieve the project objectives, the eighth and final steps is documenting the project outcome in a scholarly manners and develop recommendations for preceding research in the field. Identifying.

The following sections will discuss in depth the methodology taken to realize each subsystem of the exoskeleton, the subsections are divided as: Mechanical subsystem, Algorithm & Controller and Sensors & User Interface.

3.1.1 Project management

Table (3-1) shows the schedule for final year project part 1 and Table (3-2) shows the schedule for part 2.

Table 3-1: FYP1 Gantt chart

#	Objectives		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature Review		■	■	■	■					■	■				
2	EMG signal validation						■	■	■							
3	Drive Mechanism Identification								■	■						
4	Control Algorithm Identification												■	■		
5	Components Ordering														■	■
6	Proposal Defense										●					
7	Reports	Extended proposal						●								
		Interim Report - Draft													●	
		Interim Report														●

Table 3-2: FYP2 Gantt chart

#	Objectives		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Algorithm Development		■	■	■												
2	Components Testing					■	■	■									
3	On-chip Algorithm deployment								■	■	■	■					
4	Testing and Tuning												■	■	■		
5	Pre-sedex											●					
6	Project Viva														●		
7	Reports	Progress Report							●								
		Draft Final Report											●				
		Dissertation (soft copy)												●			
		Technical Paper												●			
		Dissertation (hard bound)															●

● Key milestone

■ Process

3.2 General System Overview

The Exoskeleton is driven by the signals sent to the muscles from the brain, the signals are measured by surface Electromyography (EMG) electrodes that are placed on the user biceps and triceps, before the signals are passed as input to the controller, the signals are amplified and processed to model the force develop in the muscle and produce a proportionally assistive torque, The wearable structure – Mechanical subsystem – is provided with sensors that are used to map the user coordinates in the 3D space. The Mapped data are then passed to the user interface in which the user can get feedback in a Game-like environment where he can practice and undergo the rehabilitation in an intuitive way. The Games will be developed in co-operation with doctors and therapists to meet the needs of the patients and help in monitoring their progress. The user Interface can be used to produce real-time reports including parameters such as time, EMG activity level and coordinates for specialist and doctors' reference. Figure (3.2) exhibits the all the subsystems: Mechanical, Electronics and User Interface with each subsystems, components and process. From inputs through controller algorithm, produced assistive torque and the interconnection with the interactive user interface.

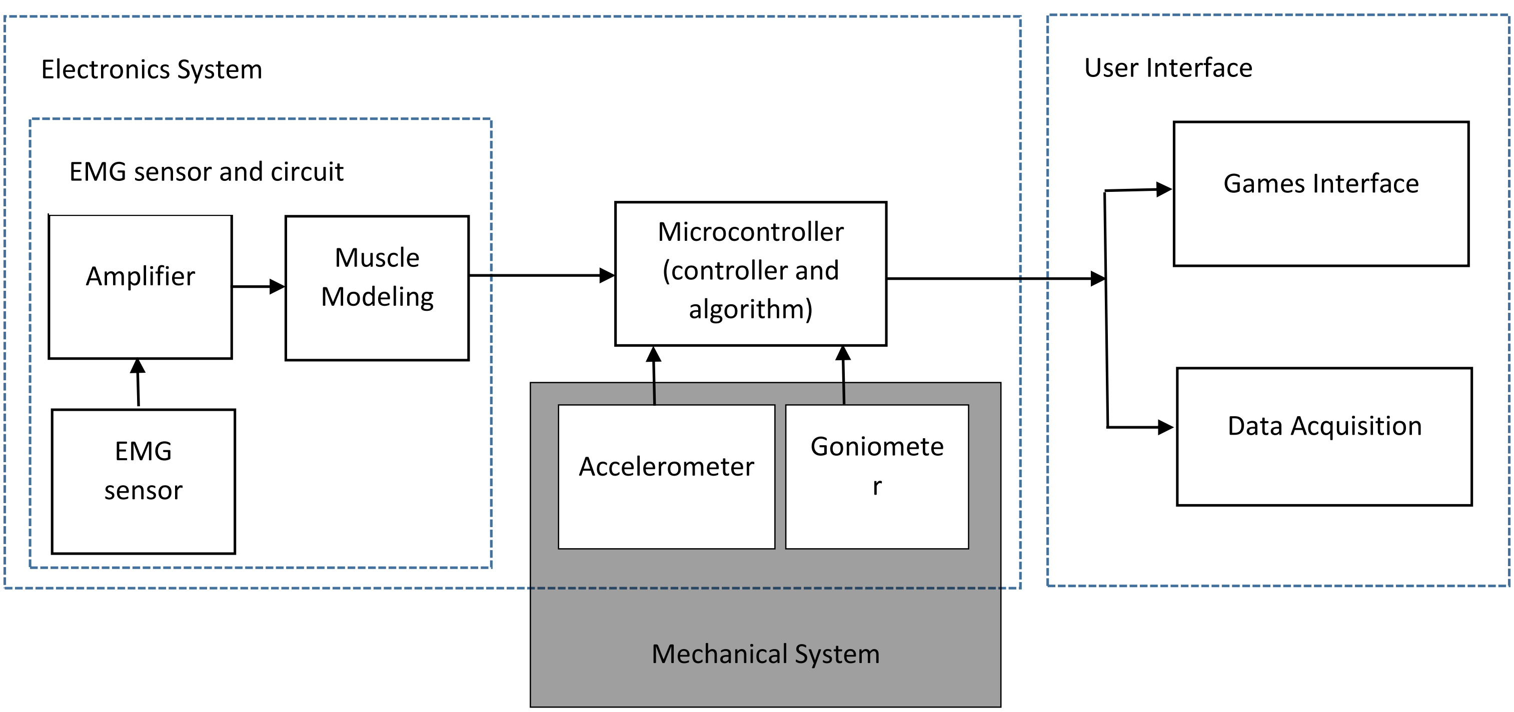


Figure 3-2: General System Overview

3.3 Mechanical Design

The mechanical components have been –firstly - designed on a CAD software: Adobe Inventor with educational license. The materials for the main structure are metal sheets and plastics. The basic structure was designed with the minimum components to ensure its lightweight. Figure (3.3) shows two 8 mm thick, 21 cm long metal sheets with on one circular end. The top part is to be attached on the upper arm with holes to attach the Motor and the gear train. The other part is to be attached on the forearm to actuate it.

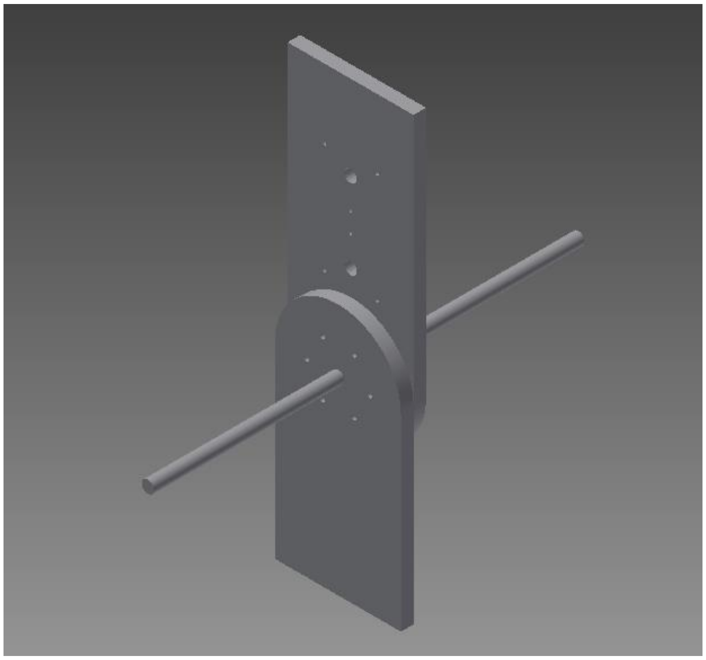


Figure 3-3: The Base Mechanical Structure of the Exoskeleton

The motor is fixed on the Arm and not on a separate compartment for the reason that the Exoskeleton presented in this study is wearable; so distributing the weight on different limb or ultimately to making the Exoskeleton support its own weight if it's developed as full suit engulfing the user body is the best way to go. Distributed weight is more reasonable that concentrated weight on the patient back – with the assumption the compartment will be worn as a bag pack. However before presenting the Motor and Gears design and selection, the Arm model which sets the floor for the selecting is shown first.

3.3.1 Arm Model

The human being body can be modeled by segments of links and hinges; whereas each segment consists of a link that rotates around Joint or Hinge (Link/hinge model) this is shown in figure (3.4).the parameters that defines the segments can be calculated as ratios of the total body parameters, one of the most used approximate segmentation table is is the clauser et al (1969) table; this approximation has a 5% error margin. [20]

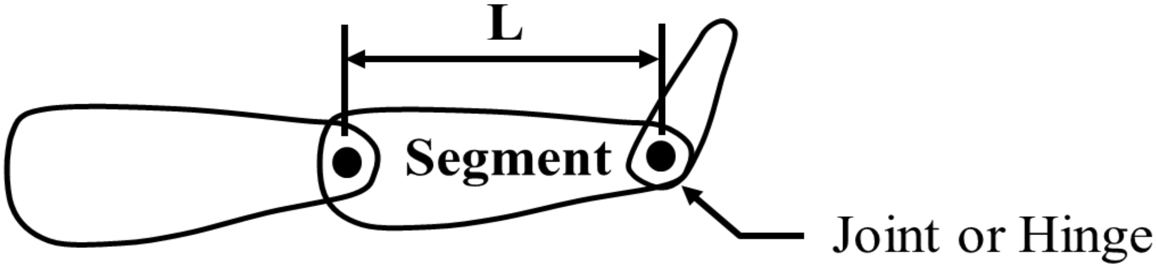


Figure 3-4: Link / Hinge Model

Most segments do not rotate about their COM (center of Mass), but about their joint on either end.

The relationship between moment of inertia about the COM and moment of inertia about the joint is given by:

$$J = Jo + m \times d^2$$

J_o = moment inertia about center of mass

d = distance between centre of mass and centre of rotation.

m= mass of segment

And the torque is given by

$$T = J \times \alpha$$

α Is the angular acceleration.

Now, to get the minimum required torque we need to calculate the total load on the system which is the forearm load and the forearm Exoskeleton segment. To estimate the load we will use Table (3-3)

Table 3-3: clauser et al table [21]

		SEGMENTAL MASS/TOTAL MASS	CENTER OF MASS/SEGMENT LENGTH		RADIUS OF GYRATION/ SEGMENT LENGTH	
Segment	**Endpoints[a] (proximal to distal)**	$(P)^b$	$(R_{proximal})^c$	$(R_{distal})^c$	$(K_{cg})^{d,e}$	$(K_{proximal})^e$
Hand	Stylion to metacarpale III	0.0065	0.1802	0.8198	0.6019	0.6283
Forearm	Radiale to stylion	0.0161	0.3896	0.6104	0.3182	0.5030
Upper arm	Acromion to radiale	0.0263	0.5130	0.4870	0.3012	0.5949
Forearm and hand	Radiale to stylion	0.0227	0.6258	0.3742		
Upper extremity	Regression equation[f]	0.0490	0.4126	0.5874		
Foot	Heel to toe II	0.0147	0.4485	0.5515	0.4265	0.6189
Foot	Sphyrion to floor	0.0147	0.4622	0.5378		
Leg	Tibiale to sphyrion	0.0435	0.3705	0.6295	0.3567	0.5143
Thigh	Trochanter to tibiale	0.1027	0.3719	0.6281	0.3475	0.5090
Leg and foot	Tibiale to floor	0.0582	0.4747	0.5253		
Lower extremity	Trochanter to floor (sole)	0.1610	0.3821	0.6179		
Trunk	Chin-neck intersection to trochanter[g]	0.5070	0.3803	0.6197	0.4297	0.5738
Head	Top of head to chin-neck intersection	0.0728	0.4642	0.5358	0.6330	0.7850
Trunk and head	Chin-neck intersection to trochanter	0.5801	0.5921	0.4079		
Total body		1.0000	0.4119	0.5881	0.7430	0.8495

From for the estimation of COM and weight of the forearm on a subject weighted 75 Kg, the following calculation was used for validation of the design:

- Forearm weight = 1.65 Kg
- COM = .21 meter
- Minimum required torque (T_r) = Weight * gravitational acc. * length

  = 1.65 kg * 9.98 m/s^2 *.21 m = 3.45 N.m

With reference to the previous calculation and the requirement of having a lightweight actuation system the motor and the gear train specifications have been identified. Figure (3.6) shows the motor used in the Exoskeleton, Maxon Motor EC 90 flat, the Motor provides a maximum continuous torque of 444 N.m and it weighs only 600 g, which makes it a suitable choice.

Figure 3-6: Maxon flat EC 90 motor - 600 g

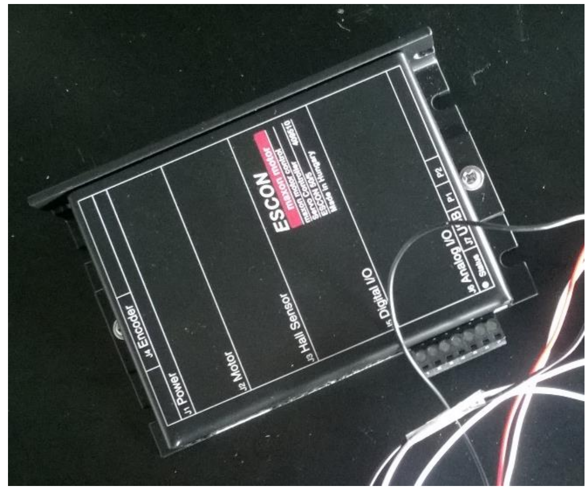


Figure 3-5: Maxon Motor Controller

The Motor comes with a PID motor controller- Figure (3.7) that can be tuning in different modes depending on the controller variable, e.g. speed or torque. The controller was tuned in the current mode (to control the torque), the relation between the current and the voltage is linear and given by the following equation:

$$T = k_t I$$

Where k_t is the torque constant = 70.5 mNm/A, the data can be found from the datasheet in Appendix III.

The motor torque is .444 Nm, and the minimum torque required is 3.45 N.m, thus the need gears ratio N is:

N >= 3.45/.444 >= 7.77

N = 8.

Based on that the two gears have been designed on inventor with 20 degree pressure angle and 15: 120 gear ratio, the gears were planned to be fabricated from Aluminum or other light alloys, due to the resources available for the first prototype the weight will be heavier than what is optimum.

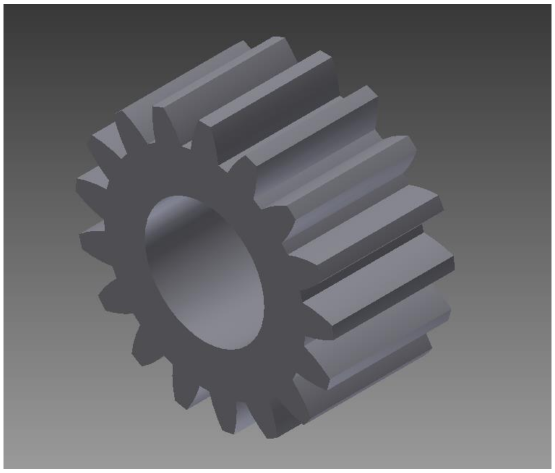


Figure 3-7: driver gear 12 teeth

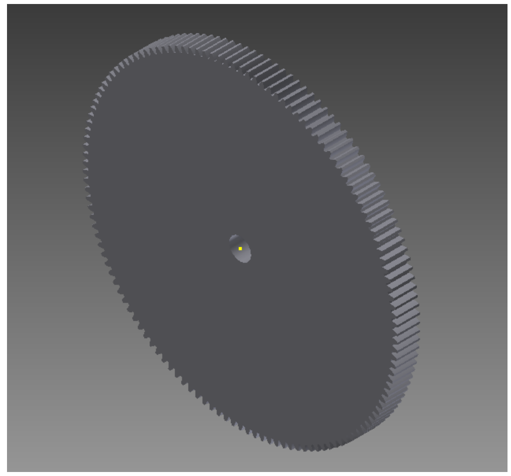


Figure 3-8: driven gear 120 teeth

Figure 3.6 shows the small gear design, with pitch diameter of 15 mm, this gear will be fixed on the motor shaft. Figure 3.7 shows the 120 mm driven gear the gear will actuate the patient's forearm, the gears are modulo 1.

3.4 Electronics System

The second main subsystem is the electronics system; which is the main focus of the study. This system includes:

- The sensors needed for measuring the input EMG signals from the muscles
- The sensors used to map the user coordinates in a 3D space including: Accelerometer and Goniometer
- The Algorithm and system controller
- The Microcontroller

3.4.1 EMG signal

Before we embark on the methodology of measuring the EMG signal from the muscles and processing the signals correctly to represent the muscle force as close as possible, the EMG signals and Force modeling technique will be briefly introduced first.

3.4.1.1 Muscle Force Model

At this point a general review of the muscle structure and neural signal is needed. The motor control part of the human's brains control the muscles by neurotransmitters Ach (acetylcholine) that passes through the ventral root of the spinal cord and to the motor end plates generating miniature end-plate potential (MEPP) which is sensed by the EMG electrodes. A motor unit is the smallest controllable unit that is innervated by a motor exon. Each muscle unit consists of fibers that consist of Fibrils, which consists of filaments of 100 A diameter. Figure (3.9) shows the described Motor unit diagram.

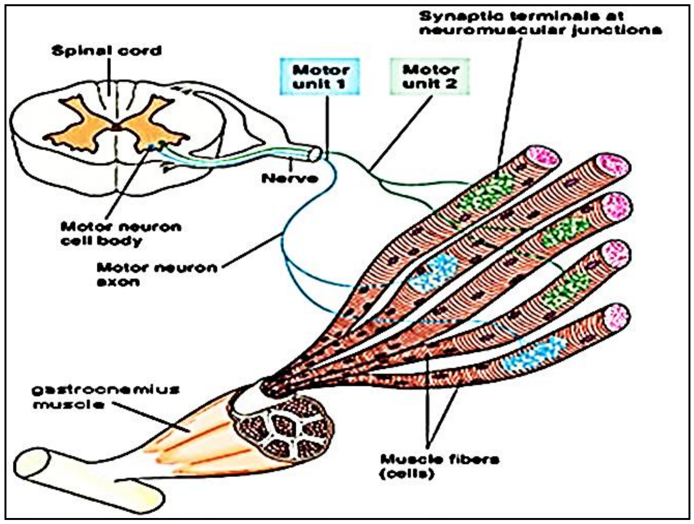


Figure 3-9: Motor unit diagram [22]

Muscle units are recruited based on theirs sizes and the force needed in certain activity. The smallest unit will be recruited first, the firing rate of the units increases with the tension until a bigger Motor unit is recruited and so on. [21] The process of motor units' recruitments is shown in Figure (3.10).

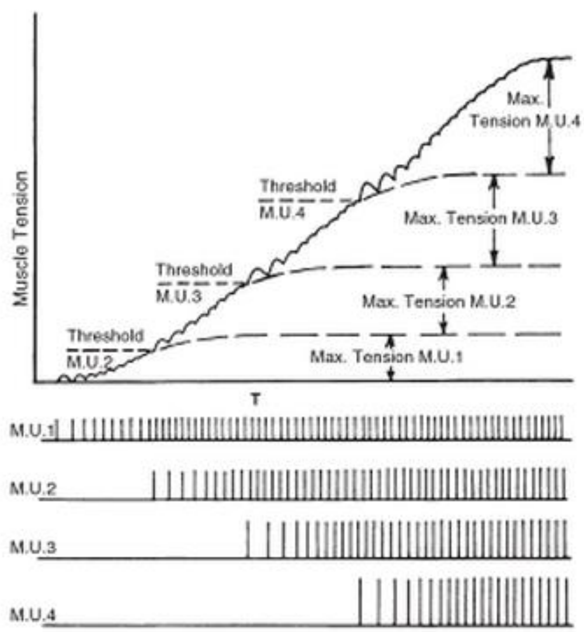


Figure 3-10: Muscle unit's recruitment based on the size prinicple

Figure (3.11) shows that a simple muscle twitching can be modeled as the impulse response of a second-order critically damped system, Contraction time depends on the motor unit. We are interested in the following muscles and contraction times: [21]

Triceps brachii	16 – 68 ms
Biceps brachii	16 – 85 ms
Medial gasttocnemius	40 – 110 ms

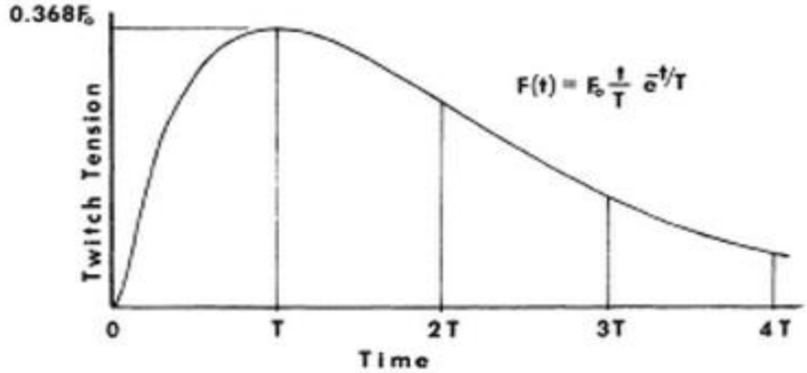


Figure 3-11: Impulse response of second-degree critically damped system [21]

3.4.1.2 Preliminary Experimental Work

As a validation step a data gathering experiments hve been carried out to draw out preliminary conclusions on the plausibility of using EMG signal as an input to the system. Delsys Tringo EMG kit has been used to sample the EMG signals form the subject biceps and triceps, the subject has moved his arm in flexion and extension three times, the readings were sampled during the activity. The data were filtered and treated using amplitude analysis on MATLAB; the result was a signal envelope to indicate the features of the flexion/extension movements in the EMG signals. Figure (3.13) indicates the EMG electrodes being fixed on the subject upper arm and figure (3-12, 3-14, 3-15) showcases sampled signals.

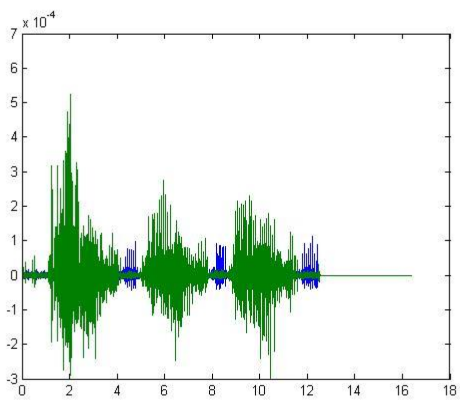


Figure 3-12: EMG signals

Figure 3-13: EMG electrodes on subject limb

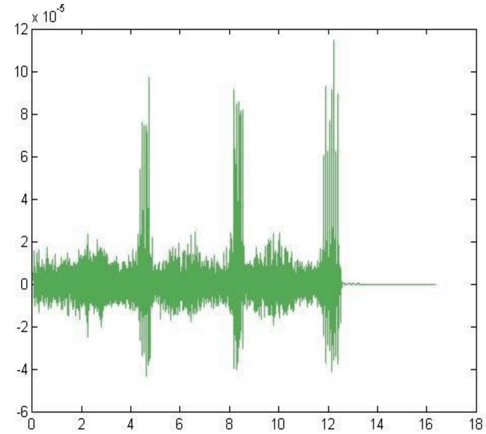


Figure 3-14: Triceps EMG signals

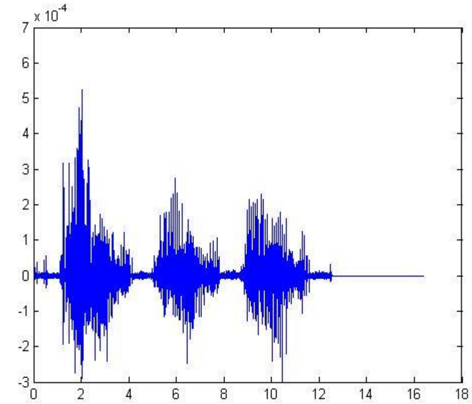


Figure 3-15: Biceps EMG signals

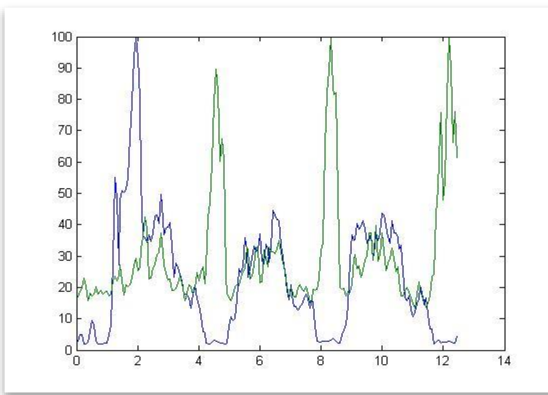


Figure 3-16: filtered EMG signals

Figure (3.16) clearly indicates the clear features and characteristics in the biceps and triceps signals when the flexion and extension are carried out. It can be inferred that in the flexion the biceps will have a profile in the range of 5-100 uV and the triceps will be in 15 to 45 uV, on the other hand on the extension the biceps is in the range is below 15uV and the triceps is higher than 45uV. These results indicate that the EMG can be used successfully to indicate the direction of the supportive motion, a control algorithm is need to model the input signal to the output torque to decide the intended torque that user is trying to achieve.

From the previous discussion it can be deducted that exists a mean to find with certainty the direction of the subject arm direction of movement, which the exoskeleton will be able to assist based on the excitation level in the biceps and triceps muscles. Referring to the previous figures this conclusion can be tabulated as such:

Table 3-4: Flexion/Extension Movement parameters

Movement	Bicep level (uV)	Triceps level (uV)
Flexion	>15	<45
Extension	<15	>45

3.4.1.3 EMG sensor and Modeling

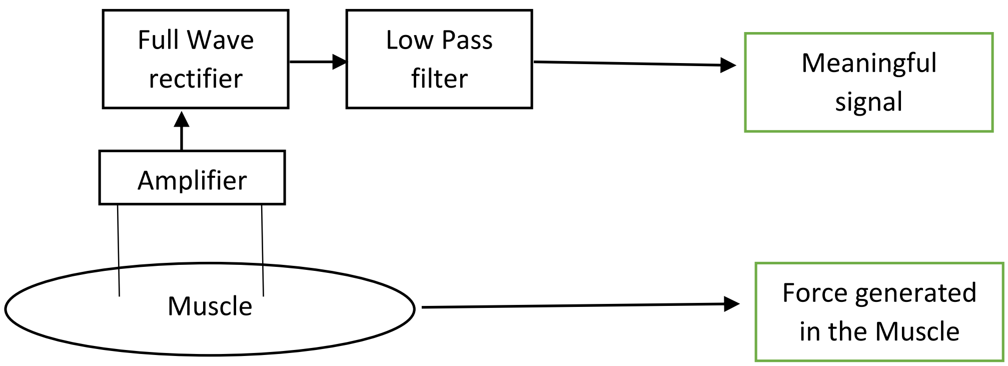


Figure 3-17: EMG signal acquisition

Based on the previous discussion, the force developed in the muscle can be modeled by a second order critically damped system as a function of muscle twitch. This is done by full rectification, the raw EMG signals are passed to a rectifier circuit and by using a low pass filter (Impulse response of second-degree critically damped system) with the appropriate cut off frequency. The full process is shown in figure (3.17). Figure (3.18) showcases the procedure on a very simplified signal i.e sinusoidal signal.

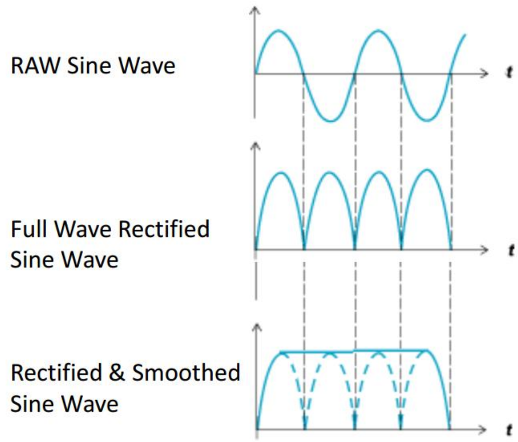


Figure 3-18: EMG signal processing by rectifying and smoothing [23]

A Three-lead Differential Muscle/Electromyography Sensor is used. The placement of the electrodes is that: one electrode is placed on the muscle belly, a second electrode is placed on the muscle end, and the last electrodes is attached next a bone to provide as a ground. The rationale behind this is; by subtracting the two electrodes signals we can clear the white noise and hum. Figure (3.19) shows the sensor used in this project to measure EMG signals from the muscles.

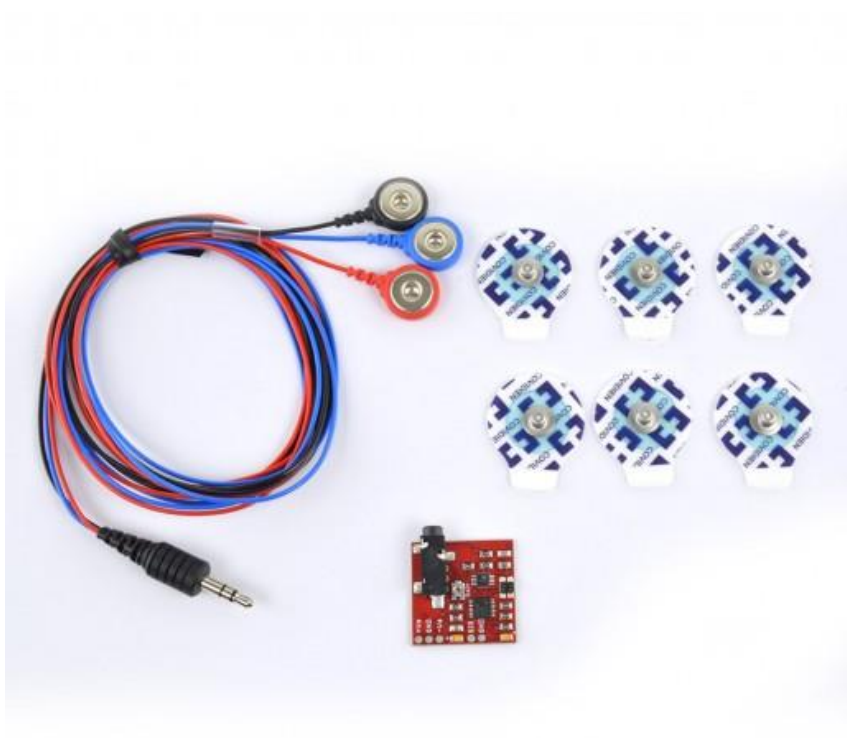


Figure 3-19: advancer technologies EMG sensor [23]

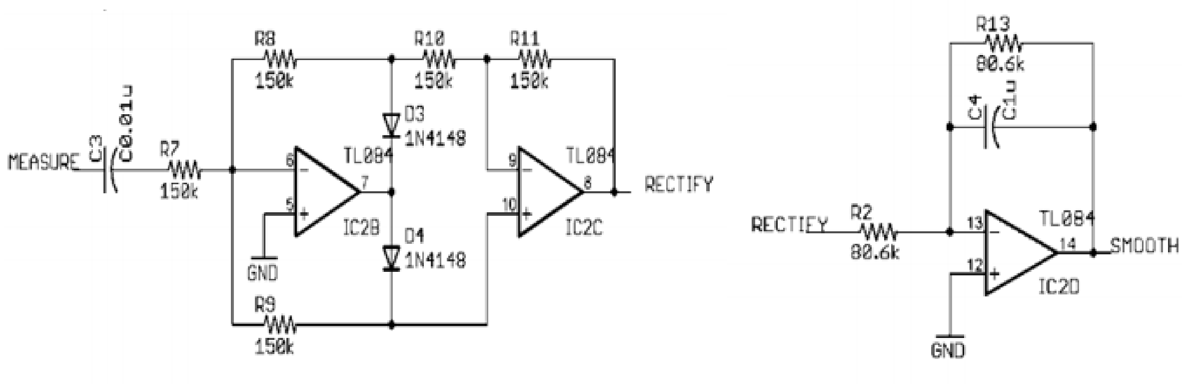


Figure 3-20: EMG processing circuits [23]

Figure (3.20) exhibits the circuits responsible for rectification and modeling the force – using a low pass filter with a cut frequency of 2Hz - from EMG signals measured by the electrodes. Prior to the circuits above exists an amplification stage with gain value of 20,700.

3.5.2 Accelerometer

An accelerometer senses accelerations in the three spatial axes, it can be used to measure the gravity components in the three X, Y, Z axes in the form of multiplicands g, this is only possible if the acceleration components are very small compared with the gravitational acceleration 9.98 m/s^2. GY-81 is used in this project, its measures the gravitational acceleration components digitally and transmit the data using I2C protocol to the microcontroller.

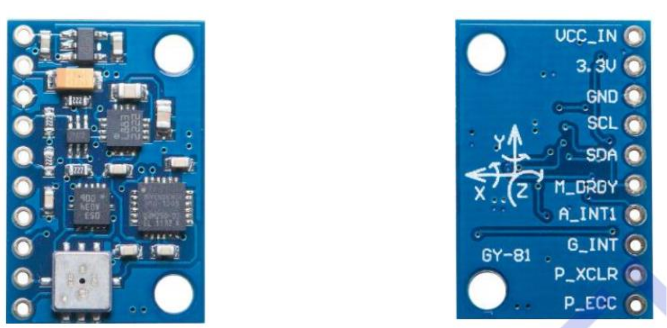


Figure 3-21: GY-81 sensor

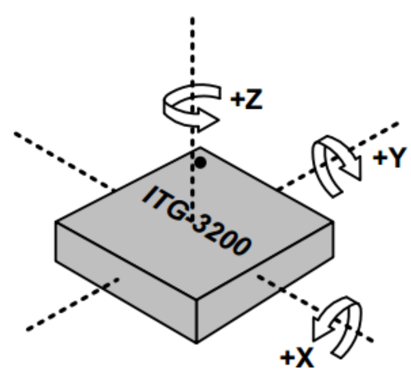


Figure 3-22: ITG 3200 rotation axis

To reduce the effect of noises produced by acceleration in the axes, the xyz components are normalized to increase calculation accuracy since the sum of the gravity components in the three axes is always one.

In this project, The GY-81 accelerometer is used to measure the pitch and Roll angles of the user upper arm segment while the segment is moving in 3D space to map the user coordinates and movement patterns.

Figure 3.21 depicts the sensor board, the board is embedded with other chips, including the I2C protocol and other peripheral chips. Figure 3.22 shows the ITG 3200 chip responsible for sensing the gravitational field Cartesian vectors. The following equations solve the system if the Roll angle - Y in figure (3.22) – is restricted to the range from -90 to 90 [24].

$$\tan \phi_{xyz} = \left(\frac{G_{py}}{G_{pz}}\right) \tag{3.1}$$

$$\tan \theta_{xyz} = \left(\frac{-G_{px}}{G_{py}\sin\phi + G_{pz}\cos\phi}\right) = \frac{-G_{px}}{\sqrt{{G_{py}}^2 + {G_{pz}}^2}} \tag{3.2}$$

θ = Pitch angle

$\emptyset$ = Roll angle

3.5.3 Goniometer

A Goniometer is basically a variable resistance that is attached to a limb to measure the joints angle [21]. A goniometer is used in this project to provide measurement of the elbow angle, in order to get feedback and map the user in the interactive games in the user interface as describe earlier in the general system overview. The Goniometer in this project scope is used to measure the elbow joint angle.

The goniometer is connected to an ADC input (1023 steps), the resistance value – Voltage across different resistances - of the variable resistance varies with joint angle. The values where calibrated and a linear regression model was developed as shown in figure (3.23).

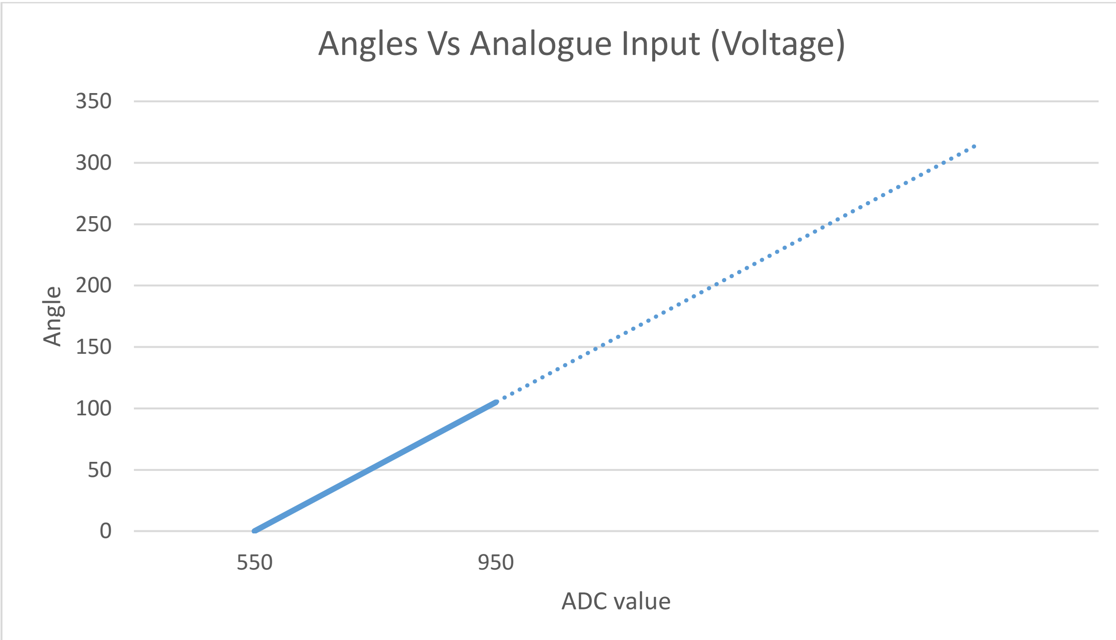


Figure 3-23: Goniometer Model

3.5.4 Arduino Mega

An Arduino Mega is a fast prototyping board, it's used as the Microcontroller- AtMega 2560 - in the project, where the Fuzzy model is programmed, the code is found in the appendix I Figure (3.24) shows the Ardunio Mega board

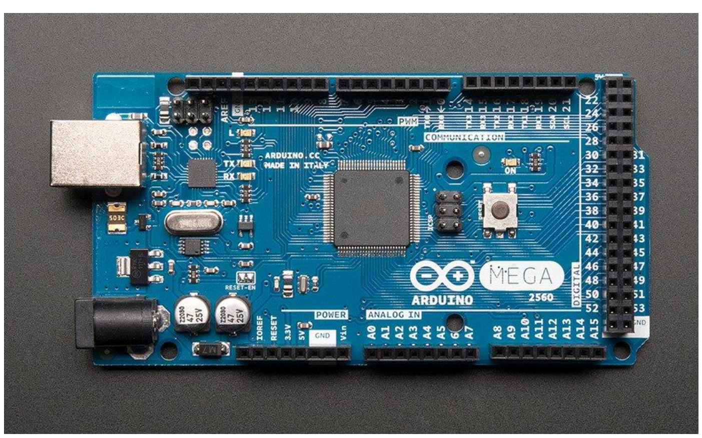


Figure 3-24: Arduino Mega Board

3.5.5 Algorithm an Controller Modeling

The System Controller consists of two important steps:

- The fuzzy logic system: the purpose of this step is to estimate the force generated in the user arm; by taking in consideration the biceps and the triceps muscles forces and the interaction of the two forces, the model is tunable via a variable resistance to control the maximum and sensitivity of the controller to the EMG signal. Fuzzy logic is used for complex systems that are hard to model and where high accuracy is not a top priority; which makes it ideal for the application. The Model is explained in details in Chapter 4.

- The Motor Controller: The motor is controlled through a conventional PID controller, the control is tuned using Maxon Motor tuning Application: ESCON, the controller is tuned after the system was fully constructed to take in account all the friction and damping components, however a preliminary simulation in MATLAB was carried out to tune the PID controller, and is presented in details in the Chapter 4.

Figure (3.25) shows the system controller diagram. The controller receives the EMG input from the surface electrodes and estimates the Torque (current: since they are directly related as presented in section 3.3) needed through the fuzzy logic rule based system, the step point is then passed to the Motor controller in the form of PWM signals – not presented in the diagram for simplification) the controlled variable which is current- is controlled by the PID controller.

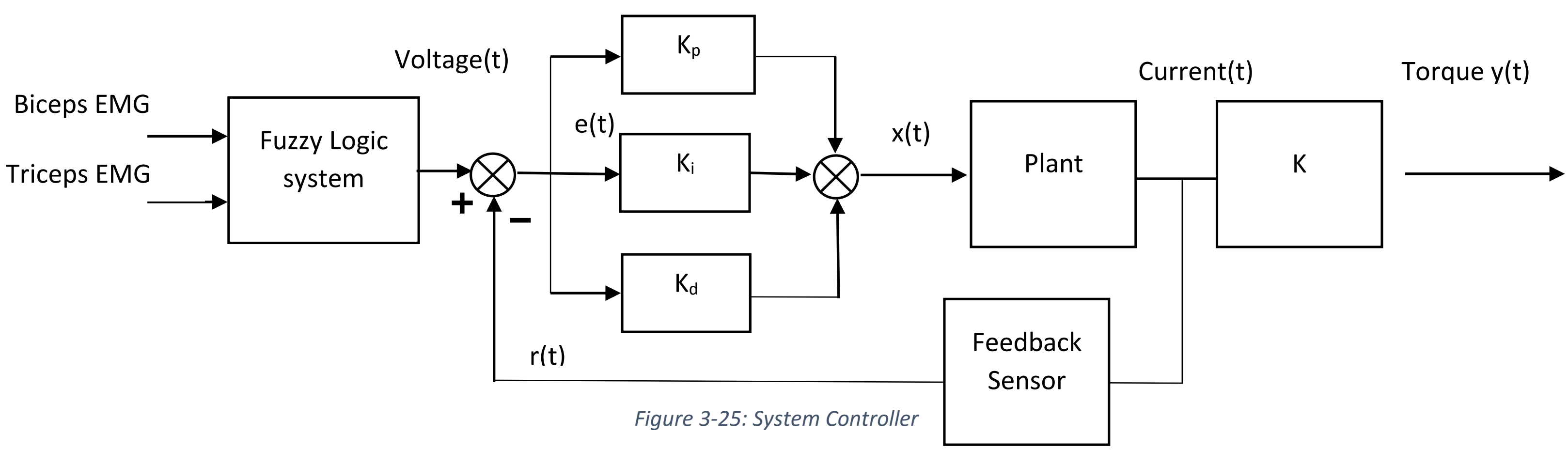


Figure 3-25: System Controller

3.5 User Interface System

With goal of increasing the patients engagement and make the rehabilitation sessions more appealing and effective an interactive user interface is developed, the interface is a gate way to 3D games, in which the user can interact with objects in different position and orientations. The system maps the user coordination in the 3D space through sensors: Accelerometer and Goniometer, the following steps and tools were used to realize the interface:

- Calibrating the Accelerometer and the goniometer to ensure accurate mapping of the user limb.
- Articulating a data transmission protocol over the serial port to create a reliable link for data transmission between the microcontroller and the PC based interface.
- Modeling the arm using the values received from the microcontroller.
- Designing the user interface through a 3D graphical tool.

Processing IDE- Figure (3.26) - was used, which has a wiring interface, like the Arduino and same style of tool functions, a setup function and a loop named draw. The language is built on C++ and used OpenGL to render the objects. And the full code is provided in the Appendix.

The system have the capability to store the data as session reports allowing to have the doctor or therapist to closely monitor the patient condition and progress. The Interface is explained in details later in Chapter 4.

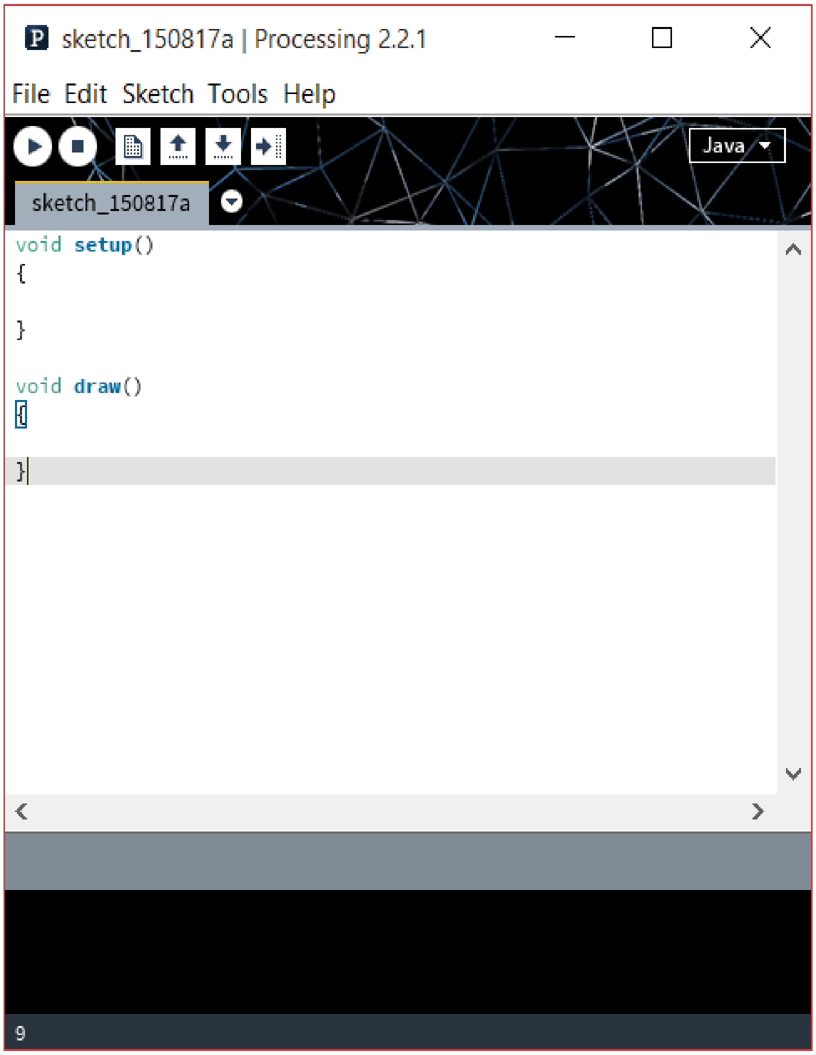


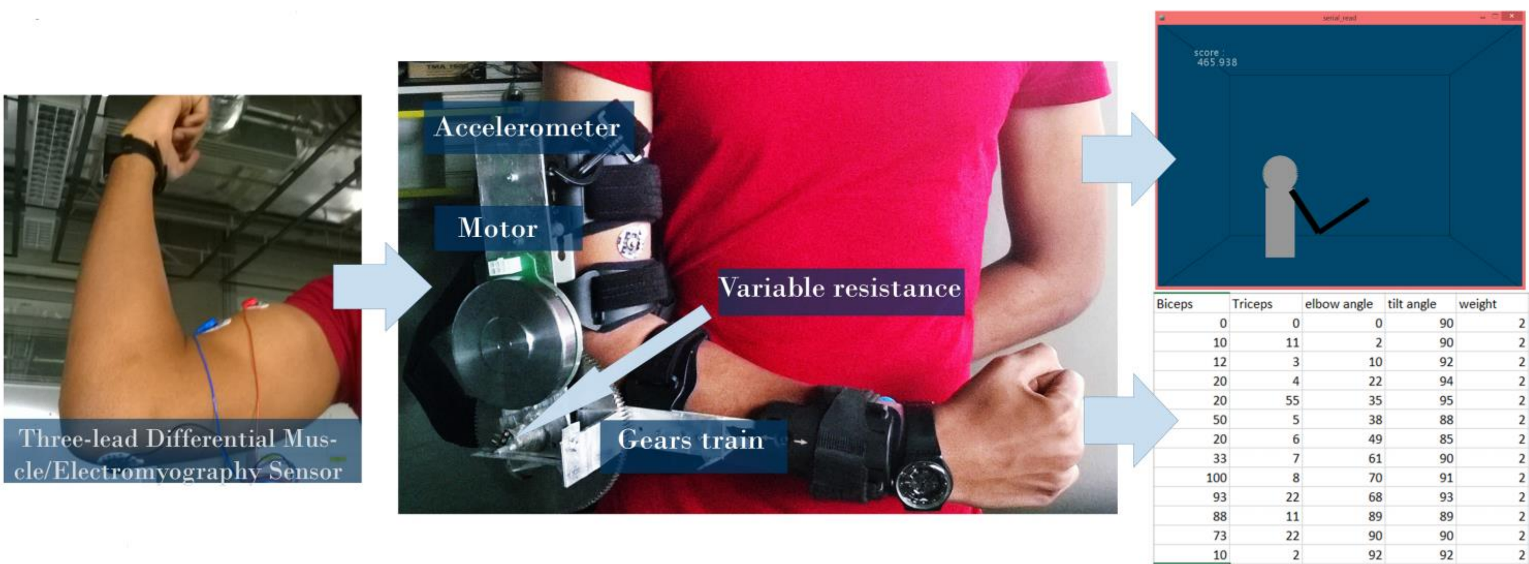
Figure 3-26: Processing IDE

Chapter 4:

4. Results and Discussions

This Chapter presents the outcome of the 8-month study following the sectioning used in the previous chapters, In this section the fabrication and assembly of the Exoskeleton is described, the Fuzzy model and controller tuning is detailed and the user interface is presented.

4.1 Final System Overview



Biceps	Triceps	elbow angle	tilt angle	weight
0	0	0	90	2
10	11	2	90	2
12	3	10	92	2
20	4	22	94	2
20	55	35	95	2
50	5	38	88	2
20	6	49	85	2
33	7	61	90	2
100	8	70	91	2
93	22	68	93	2
88	11	89	89	2
73	22	90	90	2
10	2	92	92	2

Figure 4-1: The final system overview

Figure 4.1, Shows the final system after assembly and used by a subject, the surface EMG electrodes are attached on the subject muscles – the biceps and triceps- and then the inputs are used to control the motor torque as presented in the second step after being modeled to represent the force in the muscles. The figure shows the location and setting of the accelerometer and goniometer on the exoskeleton, as they are used to control the Avatar in the game and provide real-time data acquisition system, by mapping the user coordinates with three degrees of freedom.

4.2 Mechanical Parts and Fabrication

Pertaining to the requirements and designs established in Chapter 3 – Methodology, the fabrication work has started, in this section the fabrication of the Goniometer and fixing of the Accelerometer will not be discussed.

The first part fabricated was the upper arm base structure made from lightweight metal sheet as shown is Figure (4.2), the dimension of the Motor and Gears were projected on the sheet and then holes in the appropriate points were drilled.

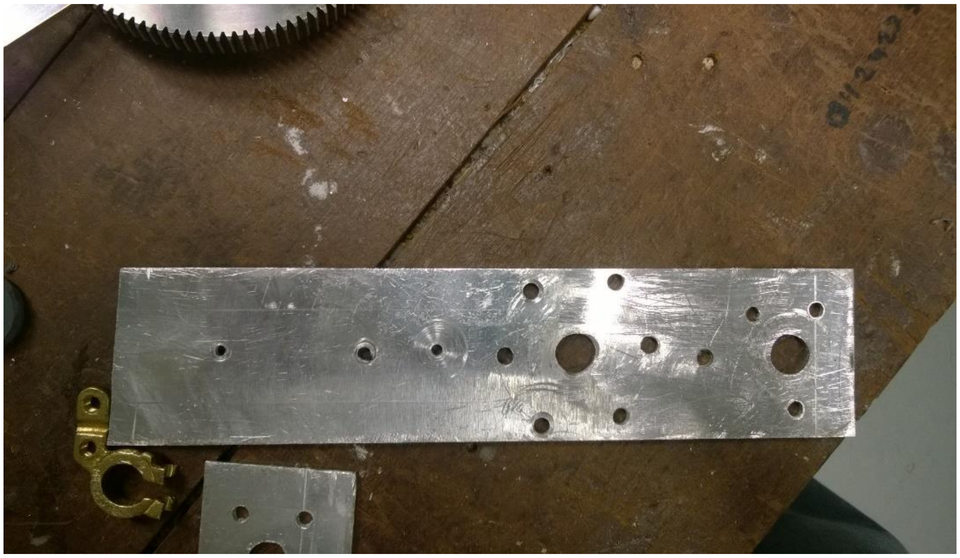


Figure 4-2: Metal sheet base structure

The next part to be fabricated was the driven gear, the gear was printed using a CAD design and a wire cut machine, the gear presented in figure (4.3) is designed in such a way to be a light as possible by cutting four big holes on the gear surface. A 12 mm shaft was produced as well, on which rotate the gears is to rotate. Couplings and wet bearings are used to trap the gear in a vertical position during its rotation. Figure (4.3) also shows the second base structure – attached to the gear by means of nuts and screws- that will be placed on the subject's forearm, where the force is transmitted to.

Figure 4-3: Driven Motor attached on the moving part of the structure

Although the driver gear was merely bought and not fabricated, it’s presented in this chapter for organization purposes, although some work was carried on to customize the gear: the bore diameter was increased from 10 mm to 12 mm-using a lathe- to fit on the motor shaft, a set screw is used for that purpose as well. Figure (4.4) exhibits the gear and the set screw.

Figure 4-4: The driver gear

After all the main parts in the mechanical structure have been fabricated, they were assembled to produce the wearable Exoskeleton mechanical structure. The structure has one degree of freedom in the elbow joint. The angle is limited from 0 – 120 degree maximum by means of mechanical movement limiters, to ensure the safety of the device. The structure currently weights around 2 Kg and it's expected to be lighter if aluminum is used for the gears instead of the currently used stainless steel. The current structure is the first prototype, more improvement can be made to achieve a 1 Kg weight divided to 600 g from the motor and 400 g from the wearable structure.

Figure (4.5) shows the mechanical structure of the robot, the structure is mounted on a brace attached to the model arm through Velcro straps. The top view shows the mounting of all the components on the structure.

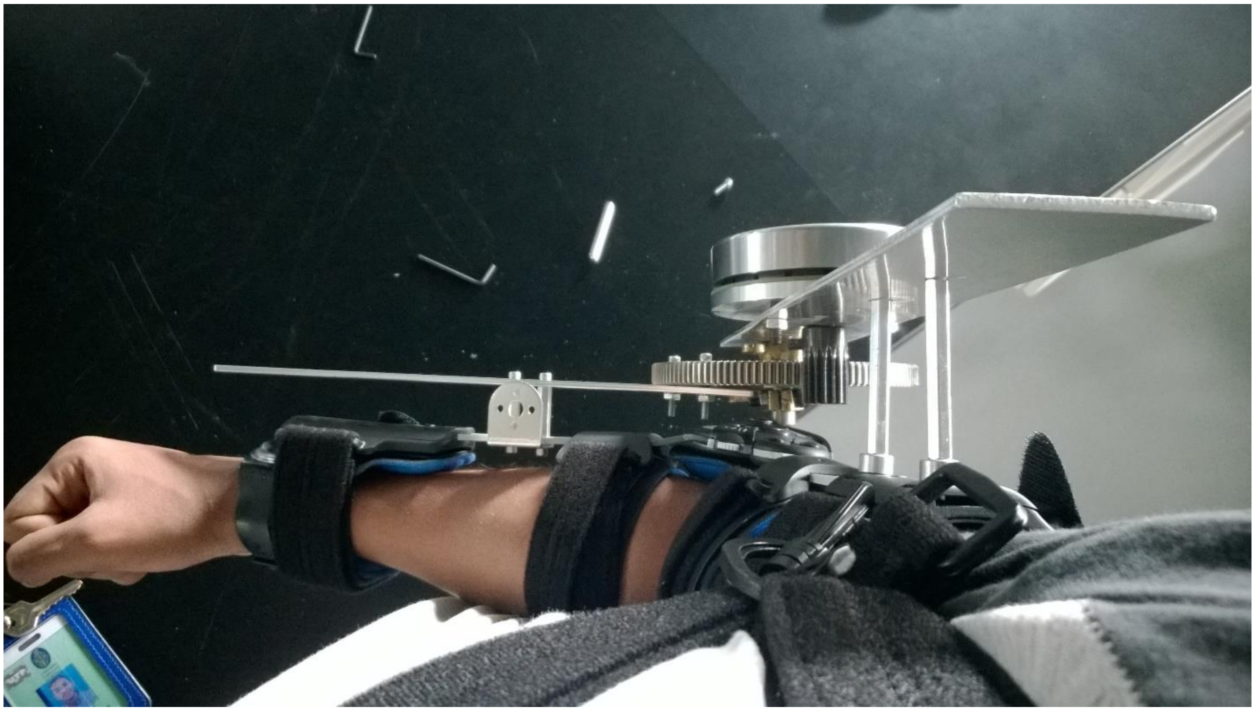


Figure 4-5: top view of the assembled base Exoskeleton Structure

4.3 Resultant Algorithm and Controller

With reference to figure (3.25) the controller is divided into two stages: The fuzzy logic rule based system and the plant PID motor controller.

4.3.1 Fuzzy System

The problem with the EMG signals as explained earlier is that, it is situation dependent in terms of the electrodes position on the users arm and the user himself (people have different muscle tissue and consequently different EMG profiles), giving attention to the problem within hand, fuzzy fitting model is excellent at adapting itself to different users by adjusting its parameters [5] [18].

The fuzzy interference System –figure (4.6)-developed is Mamdani type, it is the most famous type used since it's not computational costly, which is a merit since the system is translated and built on an Arduino board which doesn't even support threading. The board choice is due to resources limitations. Mamadani uses min for and method and max for or method.

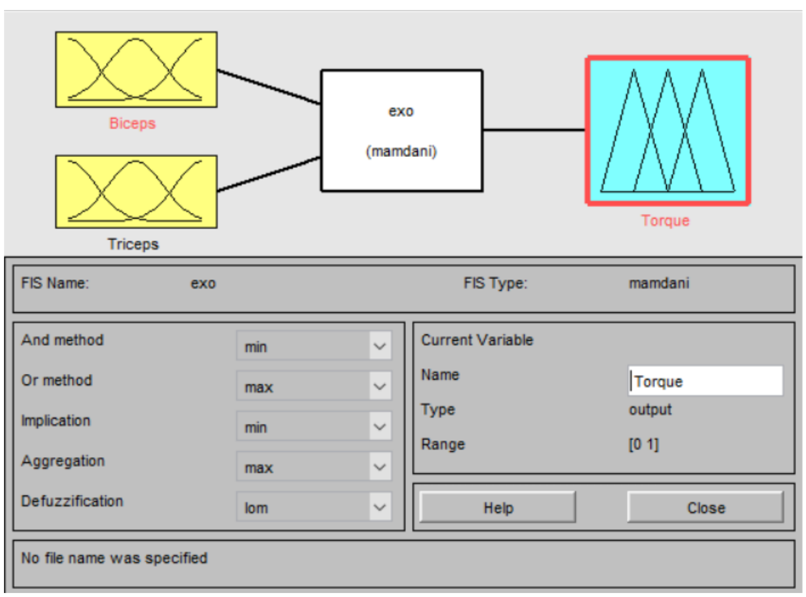


Figure 4-6: Fuzzy Logic interference system

The inputs from the Triceps and Biceps are converted into Linguistic terms and each has a triangular memberships function; the process of membership generation are carried out using an expert inference, the following are the fuzzy sets for the inputs, as shown in figure (4.7).

- High Active (HA) : 0.6 – 1.0
- Low Active (LA) : 0.2 – 0.6
- Zero (Z) : 0 – 0.2

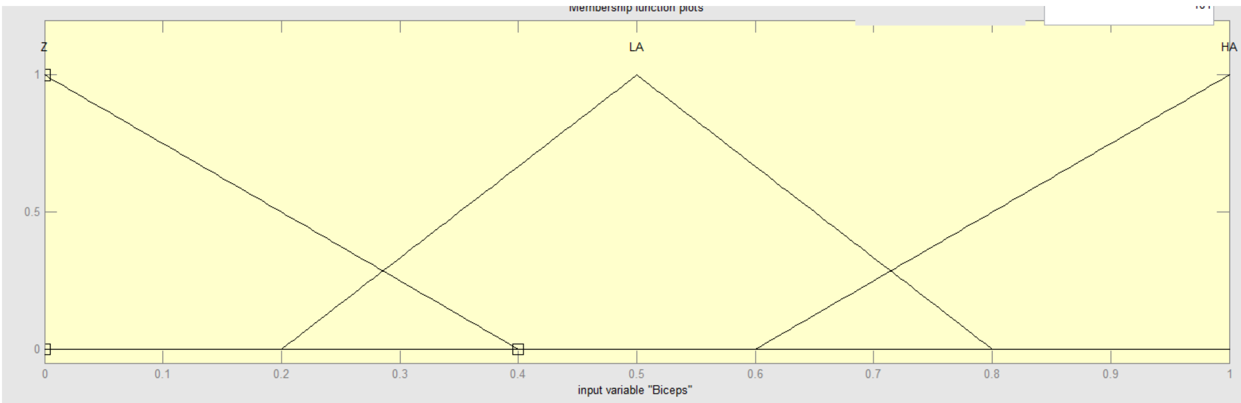


Figure 4-7: Muscles EMG memberships function

The same process is carried out to fuzzify the output (measured Torque) with the Gaussian functions and five membership's sets as shown in figure (4.8):

- Positive High (PH)
- Positive Low (PL)
- Zero (Z)
- Negative Low (NL)
- Negative High (NH)

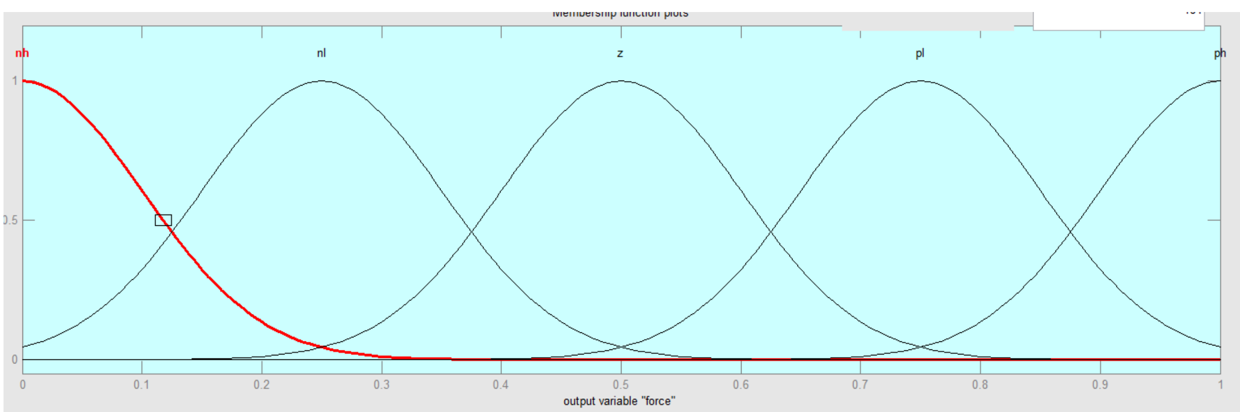


Figure 4-8: Torque/ Current memberships function

Where positive is used for flexion and negative is used for extension. A point worth noting here is that positive direction is from .5 to 1 and negative is from 0 to 0.5 in terms of the fuzzy system output.

The following is the rule-based –shown in Table (4-1) -inference system with the statement of:
IF (Biceps) AND (Triceps) THEN (Output)

Table 4-1: fuzzy rule-based system

Biceps	**Triceps**	**Output (Torque/ force)**
HA	HA	Z
HA	LA	UL
HA	Z	UH
LA	HA	DL
LA	LA	Z
LA	Z	UL
Z	HA	DH
Z	LA	DL
Z	Z	Z

Since the rules aren't contradicting or mutual exclusive – an input can have two memberships in two different set as the same time, LA & Z for e.g. the rules aggregator is a MAX operator. A simple analogy is that the rules are read using OR:

If Biceps is (HA) and Triceps is (HA) the output is (Z)

OR

If Biceps is (HA) and Triceps is (LA) the output is (UL)

OR

……… etc.

In case of AND rules a MIN aggregator is normally used. The rules are graphical presented in Figure (4.9).

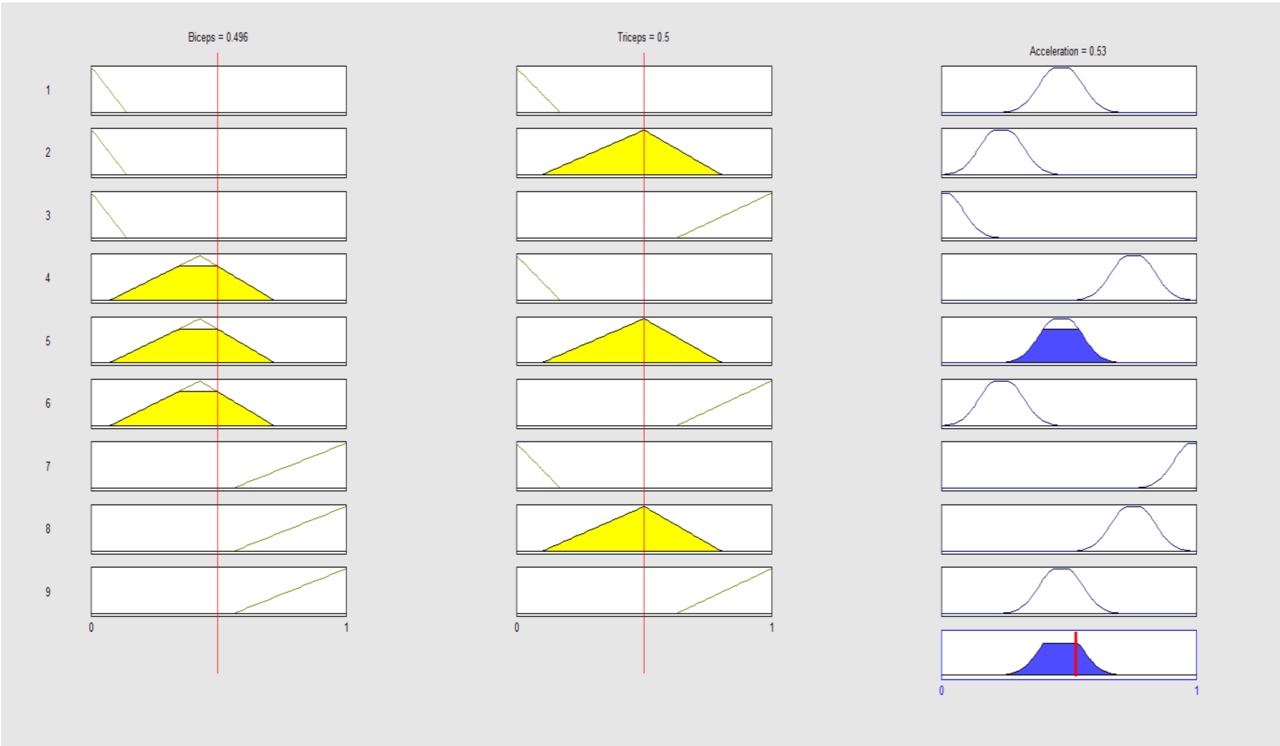


Figure 4-9: Fuzzy logic rules view

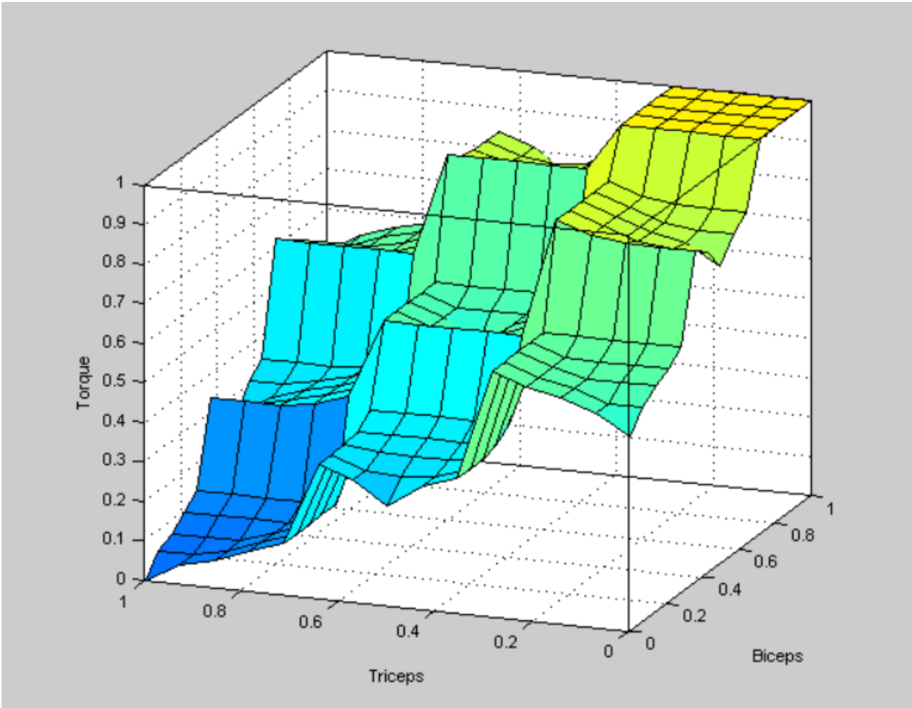


Figure 4-10: fuzzy logic surface

Figure 4.10: summaries the three dimensional Model in one graph were the value of the normalized Biceps and Triceps estimated forces, are used to predict the total system torque at the elbow joint.

4.3.2 Simulation: Motor PID Controller

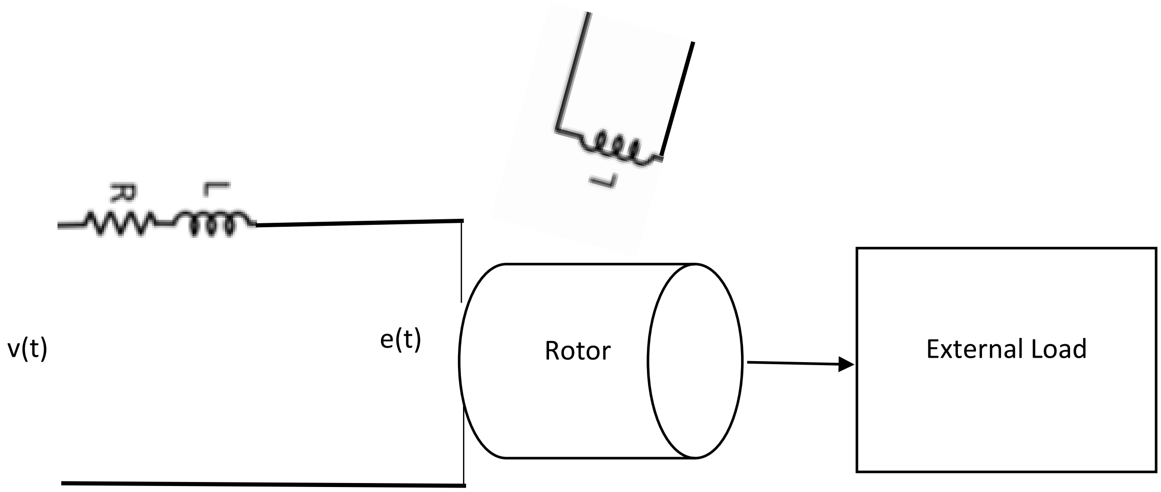


Figure 4-11 : Motor Plant

From figure (4.11) and Laplace transform:

$$V(s) = R\,I(s) + L\,s\,I(s) + E(s) \qquad (4.1)$$

But E(s) is a function of the angular velocity

$$E(s) = K_b\, s\theta_m(s) \qquad (4.2)$$

$$V(s) = R\,I(s) + L\,s\,I(s) + K_b\, s\theta_m(s) \qquad (4.3)$$

$$\theta_m(s) = \frac{V(s) - R\,I(s) - L\,s\,I(s)}{sK_b} \qquad (4.4)$$

The motor torque is a function of the total inertia. Which is a function of the rotor inertia and load, and the T

$$T = \sum Ti \tag{4.5}$$

$$T(s) = (\ Js^2 + \ D\,s\ )\theta_m(s) \tag{4.6}$$

$$T(s) = \ K_t I(s) \tag{4.7}$$

$$K_t\ I(s) = (\ Js^2 + \ D\,s\ )\theta_m(s) \tag{4.8}$$

From equation number (4.4) and (4.8) and by assuming the inductance and damping is small, we get the following transfer function (since the torque can be represented in terms of current we can use the current as the output variable and simplify the Controller block diagram

$$\frac{I(s)}{V(s)} = \frac{Js + D}{[\ RJs + RD + \ K_b K_t\ ]} \tag{4.9}$$

Where:

I	Current	
V	Input Voltage	
K_t	Torque constant	0.0705 N.m/A
K_b	Back Emf	24/ 334.06 = 0.0718
J_m	Motor inertia	0.000306 kg-m^2
J_L	Load inertia to motor side	0.105/64 = 0.00165 kg-m^2
$J = J_L + J_m$	Total inertia	0.001961 kg-m^2

R	Resistance	0.343
D	Damping	0.0144519112652648 N.m s/rad
w	No load speed	334.05601845 rad/s
V_n	Nominal Voltage	24

s

$$\frac{I(s)}{V(s)} = \frac{0.001961s + 0.01445}{[\,0.00672s + \ 0.0102\,]}$$

The transfer function and the PI controller where implement in MATAB to tune the controller and observe the performance as shown in figure (4.12)

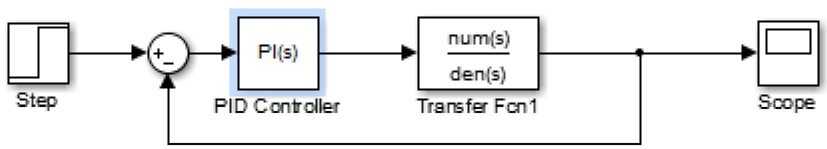


Figure 4-12: Simulink function blocks

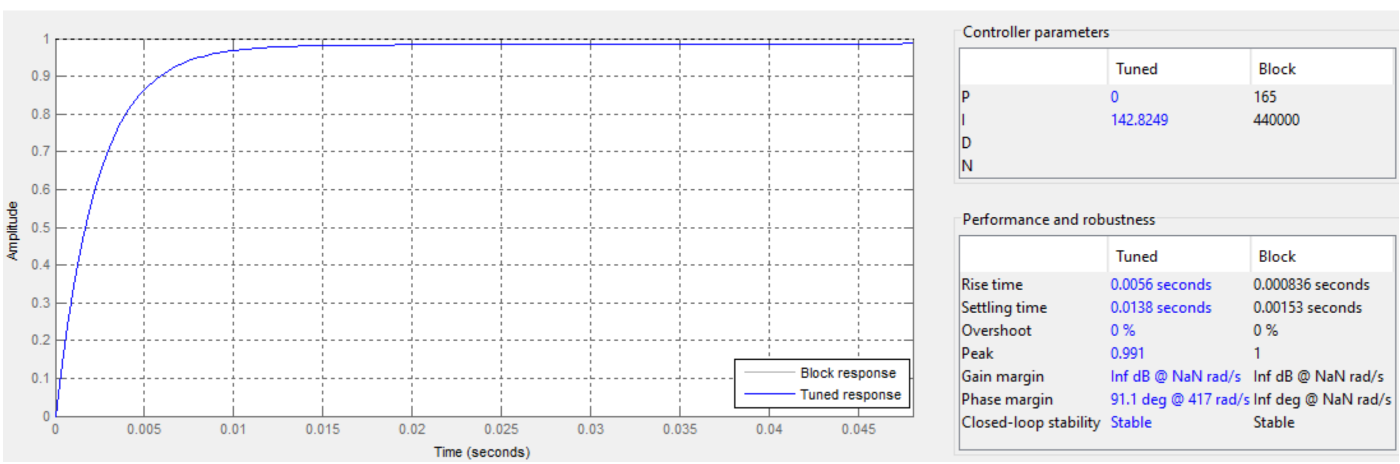
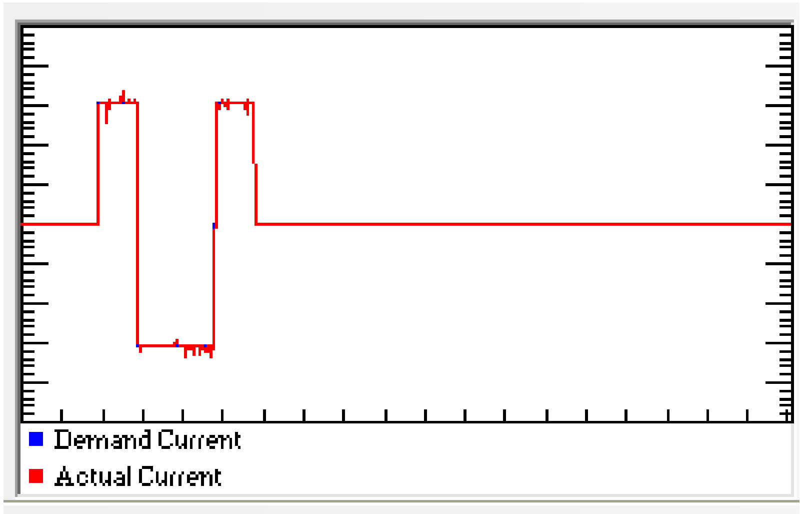


Figure 4-13: MATLAB Tuner and results

Figure (4.13) shows the tuned system controller in blue, the grey plot represents the tuned controller using Maxon ESCON, in a real time assessment process and Kp = 165 and Ki 440000. Figure (4.14) exhibits the real-time tuned controller.



Kp	Ki
165	440000

Figure 4-14: Real-time tuned Controller

We can reconcile the difference between the actual and the simulation results, by stating that friction, damping and other variables were not taken into account in the simulation, Nevertheless referring to figure (4.14) we see that the actual tuning parameters gives a good system response despite the overshoot and the long settling time.

4.4 The User Interface

One of the challenges for a complete and meritorious rehabilitation session is getting the patient to engage in the rehabilitation session and exert enough effort for long time periods. The patient gait and correct movement pattern is crucial for the patient to regain the normal motor and movement patterns. This project aspires to achieve engagement and correct deviated or unordinary movement patterns through gamification. Gamification is the use of games as tool to achieve a primary goal – in this scope the primary goal rehabilitation.

A set of games has been developed, it models the patient body and provides a real-time graphical feedback for the patient arm coordinates and kinematics through solving the accelerometer X, Y, Z axes inputs and goniometer joint angle measurement. The games graphical interface is based on OpenGL and is programmed using processing IDE.

As shown in figure (4.15) The Game receives data from the accelerometer and the goniometer attached on the Exoskeleton, the accelerometer provides two degrees of freedom in the elbow and the goniometer provides one degree of freedom.

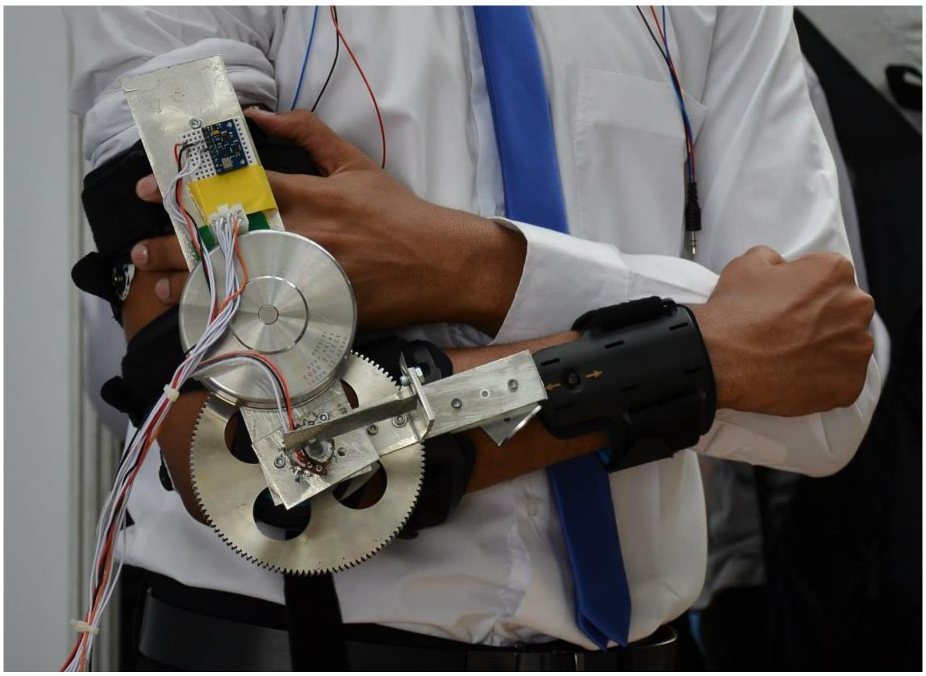


Figure 4-15: setting of the Accelerometer and goniometer

The following equations (code) are used for calculating the Pitch angle in range from (0 – 360) and Roll angle in the range from (- 90 to 90) the accelerometer is insensitive to yaw rotation, since it's about the gravitational field.

```
x_angle= atan2(ngy,ngz);

y_angle=atan(ngx/sqrt(sq(ngz)+sq(ngy)));
```

And the elbow joint angle is calculated based on the linear model presented in section 3.5.3.

The data are sent in a CSV (comma separated values) from the Ardunio and used to rotate the Arm segments of an Avatar in the game interface as shown in figure (4.16). The data are easily accessed and can be saved directly to excel sheets using tools such as Coolterm. The full code is provided in Appendix II.

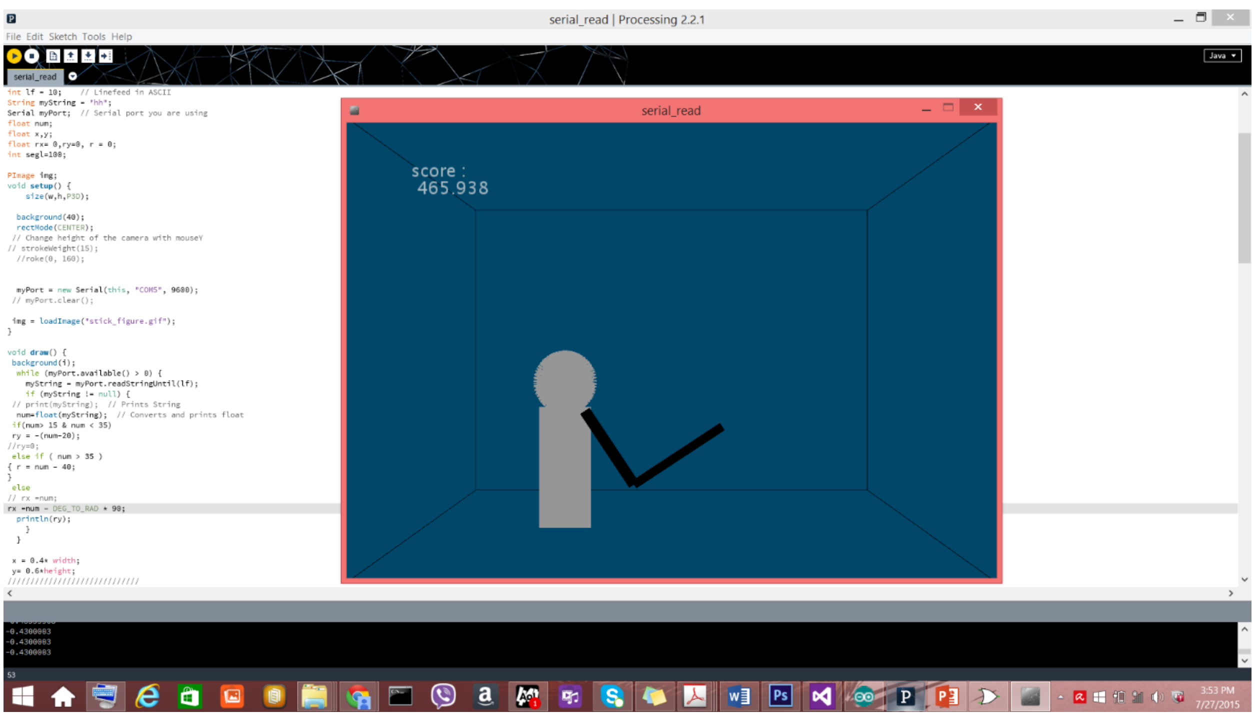


Figure 4-16: Interactive Game interface

Chapter 5:

5. Conclusion and Recommendations

This Chapters concludes the project by reviewing the objects and validating if they are met or not, the chapter present the social motivation behind the project and proposes recommendation for future work.

5.1 Conclusion

In conclusion, EMG signals from the muscles are chosen to be the main input to the Exoskeleton with reservations to its nosiness and uncertain nature, this reservation was ameliorated with the use of a fuzzy logic controller, the fuzzy logic is also used here because of the complexity found in modeling the human arm .To qualify the rehabilitation even more an interactive user interface has been developed, this interface is meant to achieve two purposes: first, to increase the patient engagement in the rehabilitation. Secondly, to increase the effeteness of the rehabilitation by providing real-time data real at any time to be analyzed by doctors for close and deeper monitoring.

In the process of articulating the mechanical design, the average human's torque was estimated and the required Exoskeleton torque was developed based on it. Aluminum and Plastic were chosen as base materials because they are light weighted and malleable, DC brushless motors are chosen to be the actuators with gears train to produce the desired torque output.

In conclusion the following objectives have been met:

•To review and chose an algorithm/mechanism to enhance the EMG signals as input.

•To ensure that the patient is exerting enough effort in the system.

•To produce a reliable model for the Exoskeleton system.

•To design a cheap, lightweight wearable exoskeleton to help patients in their daily activities.

5.2 Societal Benefits and Impact

WAvE: Wearable Arm Exoskeleton (v = valiant) has been chosen as the commercial name for the Exoskeleton system developed in this study. WavE is meant to benefit the society by:

- WAvE provides patients with Hemiparesis stroke which is the most common stroke with an easily available rehabilitation process.
- It provides doctors and therapists with real-time data on the patients' condition, and ensure close monitoring over the rehabilitation progress.
- It provides a user friendly and fun interface to encourage patients to practice.
- Lightweight and rigid build with potential to improve further
- It reduces the number of therapists that are needed for rehabilitation and protect them from suffering from MSD resulting from rehabilitation.
- It has the potential to be a cost-effective and readily available rehabilitation machine, accessible to people in developing countries and worldwide.

5.3 Recommendations for Future Work

Although the study is really promising, more work is needed to be carried out before the Exoskeleton is ready to be made available for the public. The following recommendations are most important:

•To carry out thorough tests on patients with different MSDs for an ample period of time, to ensure the effectiveness and quality of the rehabilitation provided by the exoskeleton.

•To research and gain fund to fabricate a lighter mechanical structure using materials such as copper alloys and fibers.

•To design more interactive games in co-operation with professional therapists and specialized doctors.

•To study the possibility of implementing a neural-fuzzy network to reorganize itself based on the user movements, to produce an even smoother response (model) with time.

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Appendices

Appendix I

Fuzzy system code in Arduino board:

```
#include "Arduino.h"m

#include "LiquidCrystal.h"

#include <math.h>

LiquidCrystal lcd(8, 9, 4, 5, 6, 7);

///////////////////////////////////////////////////////////

const int bip = A2;

const int trp = A13;

const int pwmp = 11;

///////////////////////////////////////////////////////////

float Zba = 0;

float Zbb = 0;

float Zbc = 0.4;

float Lba = 0.2;

float Lbb = 0.5;

float Lbc = 0.8;

float Hba = 0.6;

float Hbb = 1;

float Hbc = 1;
```

```
int flag =0;

float b=0.6;
float t= 0;

float mhb = 0, mlb =0, mzb = 0;
float mht = 0, mlt =0, mzt = 0;

float r1 = 0, r2 = 0, r3 = 0, r4 = 0, r5 = 0, r6 = 0, r7 = 0, r8 = 0, r9 = 0;
float nh = 0, nl = 0, z = 0, pl = 0, ph = 0;

/////// intersection points of the output fuzzy memberships !!

float  p1 =0, p2 = 0.25, p3 = 0.5, p4 = 0.75, p5 = 1;

float m = 0, s= 0.1 ;

float force = 0;

float forceo = 0;

void setup() {
  // put your setup code here, to run once:
  lcd.begin(16, 2);
  Serial.begin(9600);
  Serial.println("fuzzy");
}
```

```
void loop() {

///////////////////////////////////////////////

//
b = analogRead(bip)/1023.0;
//t = analogRead(trp)/1023.0;

lcd.setCursor(0,0);
lcd.print(b);

lcd.setCursor(8,0);
lcd.print(t);
///////////////////////////////////////////////

  mhb = H_bicep(b);
  mlb = L_bicep(b);
  mzb = Z_bicep(b);

  Serial.println("biceps:");
  Serial.print(mhb);
  Serial.print(",");
  Serial.print(mlb);
  Serial.print(",");
  Serial.println(mzb);

  mht = H_bicep(t);
  mlt = L_bicep(t);
  mzt = Z_bicep(t);
```

```
Serial.println("triceps:");
Serial.print(mht);
Serial.print(",");
Serial.print(mlt);
Serial.print(",");
Serial.println(mzt);

//////////////////////////////////rules of output nh

r1 = min (mzb,mht);

nh = r1;

//////////////////////////////////rules of output nl

r2 = min (mlb,mht);
r3 = min (mzb,mlt);

nl = max(r2,r3);


//////////////////////////////////rules of output z

r4 = min (mzb,mzt);
r5 = min (mlb,mlt);
r6 = min (mhb,mht);

z = maxx (r4,r5,r6);
```

```
////////////////////////////////rules of output pl

r7 = min (mhb,mlt);
r8 = min (mlb,mzt);

pl = max(r7,r8);

////////////////////////////////rules of output ph

r9 = min (mhb,mzt);

ph = r9;

/////////////////////////////////////////////////

force = aggrde(p1,p2,p3,p4,p5,nh,nl,z,pl,ph);
force = 100*force;

if (force >= 50)
{
forceo = map (force,50,100,20,240);
lcd.setCursor(8,1);
lcd.print(forceo);
}
if (force < 50 )
{
forceo = map (force,50,0,20,240);
```

```
 lcd.setCursor(8,1);
 lcd.print(-forceo);
 }
 Serial.println("force:");
 Serial.println(force);
 analogWrite(pwmp,forceo);
 Serial.print("\t output = ");
 Serial.println(forceo);

 //lcd.setCursor(0,1);
 //lcd.print(force);



 delay (1000);

}

//////////////////////////////////////////////////////////
float H_bicep(float x)
{
 if (( x >= Hba)&& (x < Hbb))
 {
  return slope( Hba , Hbb, 0, x);
 }
  else if (( x >= Hbb)&& (x < Hbc))
 {
  return slope( Hbb , Hbc, 1, x);
 }
 else
```

```
  return 0;

}
////////////////////////////////////////////////////////////
float L_bicep(float x)
{
  if (( x >= Lba)&& (x <Lbb))
  {
  //  Serial.println("Dd");
   return slope( Lba , Lbb, 0, x);
  }
   else if (( x >= Lbb)&& (x < Lbc))
  {
   return slope( Lbb , Lbc, 1, x);
  }
  else
  return 0;
}
////////////////////////////////////////////////////////////
float Z_bicep(float x)
{
  if (( x >= Zba)&& (x <Zbb ))
  {
   return slope( Zba , Zbb, 0, x);
  }
   else if (( x >= Zbb)&& (x < Zbc))
  {
   return slope( Zbb , Zbc, 1, x);
  }
```

```
  else
  return 0;
}
////////////////////////////////////////////////////////////

float slope( float x , float y, int t, float s)// x is x1
{

  if ( t == 0) // ascending type
  {

   float m = 1/ ( y-x);
   return m*(s-x);
  }

  else // descending type
  {
    float m = -1/ ( y-x);
   return m*(s-y);
  }


}
////////////////////////////////////////////////////////////

float maxx (float x , float y , float z)
{
  if ((x >= z) && (x >= y))
  {
```

```
   return x;
  // break;
 }
  if ((y >= x) && (y >= z))
 {
   return y;
   //break;
 }
  if ((z >= x) && (z >= y))
 {
   return z;
   //break;
 }
}
//////////////////////////////////////////////////////////////////////

float aggrde ( float p1, float p2, float p3, float p4, float p5, float nh, float nl, float z, float pl, float ph)
{
 // using largest of maximum
 float buff = maxx (nh,nl,z);
 float buf =  maxx (buff,ph,pl);
 Serial.print("buf:");
 Serial.println(buf);
 Serial.print("rule:");
 if ( buf == nh )
   { Serial.println("nh");
   return igaus ( buf, p1);
   }
```

```
  if ( buf == nl )
    {Serial.println("nl");
    return igaus ( buf, p2);
    }

  if ( buf == z )
    {Serial.println("z");
    return igaus ( buf, p3);
    }

  if ( buf == pl )
    {Serial.println("pl");
    return igaus ( buf, p4);
    }

  if ( buf == ph )
    {Serial.println("ph");
    return igaus ( buf, p5);
    }

}

/////////////////////////////////////////////////////////////////

float igaus (float y,float m)
{
  float x1 = m - sqrt(2) * s * sqrt ( log (1/y) );
  float x2 = m + sqrt(2) * s * sqrt ( log (1/y) );
  float x = max (x1,x2);
```

```
 // lom
  if ( x > 1 )
  x = 1;
  if (x < 0 )
  x = 0;

  return x;


 // return (x1+x2)/2;
}

////////////////////////////////////////////////////////////////

float mapp(float x, float in_min, float in_max, float out_min, float out_max)
{
  return (x - in_min) * (out_max - out_min) / (in_max - in_min) + out_min;
}
```

Appendix II

The user Interface codes:

Arduino Code:

```
#include <Wire.h>
#include <math.h>
#include <BMA180.h>

BMA180 bma180;
int  count=0;
  float   axv=0, ayv=0,azv=0;
  float   ax=0, ay=0,az=0;
  float xAng=0,yAng =0, zAng =0;
  float g=0;
  float gx=0;
  float gy=0,gz=0;
  float ngx=0,ngy=0,ngz=0;

  const int analogInPin = A15;  // Analog input pin that the potentiometer is attached to
//const int analogOutPin = 9; // Analog output pin that the LED is attached to

int sensorValue = 0;        // value read from the pot
int outputValue = 0;
void setup()
{
 int id,version;

 Wire.begin();
 Serial.begin(9600);

 bma180.bma180SoftReset();
 bma180.bma180EnableWrite();

 bma180.bma180GetIDs(&id,&version);

 bma180.bma180SetFilter(bma180.F10HZ);
 bma180.bma180SetGSensitivty(bma180.G1);
 delay(100);
}
```

```
void loop()
{
   bma180.bma180ReadAccel();
gx=bma180.bma180GravityX();
gy=bma180.bma180GravityY();
gz=bma180.bma180GravityZ();

g= sqrt(sq(gx)+sq(gy)+sq(gz));

ngx= gx/g;
ngy= gy/g;
ngz = gz/g;



//ax= atan2(ngy,ngz);
//ay=atan(ngx/sqrt(sq(ngz)+sq(ngy)));




ay=atan2(ngx,ngy);
ax=atan(ngz/sqrt(sq(ngy)+sq(ngx)));

//ry in processing !!
  Serial.println( 20+ ax );
 // rx in processing !
 Serial.println(ay );
 /*

 Serial.println(20+ ax -  DEG_TO_RAD * 90 );

 Serial.println( ay -  DEG_TO_RAD * 90);
 */
 ////////////////////////////////////////
   // read the analog in value:
  sensorValue = analogRead(analogInPin);
  // map it to the range of the analog out:
  outputValue =  map(sensorValue, 550, 950, 0, 105);
  // change the analog out value:
 // analogWrite(analogOutPin, outputValue);

  // print the results to the serial monitor:
//  Serial.print("sensor = " );
```

```
 // Serial.print(sensorValue);
//  Serial.print("\t output = ");
// Serial.println(outputValue);
 Serial.println(40+(DEG_TO_RAD * outputValue));


   delay(200);
}
```

Processing IDE Code

```
import processing.serial.*;

 //int x =0;
int h = 700;
int w = 1000;
int wall = 500;
int llaw= 700;
//color i = color(0, 75, 112);
color i = color(0,71,106);


int lf = 10;    // Linefeed in ASCII
String myString = "hh";
Serial myPort;  // Serial port you are using
float num;
float x,y;
float rx= 0,ry=0, r = 0;
int segl=100;

PImage img;
void setup() {
   size(w,h,P3D);

  background(40);
  rectMode(CENTER);
 // Change height of the camera with mouseY
// strokeWeight(15);
  //roke(0, 160);


  myPort = new Serial(this, "COM5", 9600);
```

```
 // myPort.clear();

 img = loadImage("stick_figure.gif");
}

void draw() {
 background(i);
  while (myPort.available() > 0) {
    myString = myPort.readStringUntil(lf);
    if (myString != null) {
 // print(myString);  // Prints String
  num=float(myString);  // Converts and prints float
 if(num> 15 & num < 35)
 ry = -(num-20);
//ry=0;
 else if ( num > 35 )
{ r = num - 40;
}
 else
// rx =num;
rx =num - DEG_TO_RAD * 90;
  println(ry);
    }
  }

 x = 0.4* width;
 y= 0.6*height;
/////////////////////////////
textSize(20);
//text("word", 100 ,300);
fill(220,220,220, 204);
text("score : ", 200, 150,0);
text(x+cos(rx)*segl, 200, 170,0);
//fill(0, 102, 153, 51);
//text("word", 100, 390);




pushMatrix();
translate(0,0,-100);
stroke(150,150,150, 255);
strokeWeight(80);
segemet(x-50,y+10 ,0,0,0,5000);
```

```
translate(0,-35);
//translate(58, 48, 0);
//lights();
//sphereDetail(100);
sphere(8);
 popMatrix();


 stroke(0);




 pushMatrix();
// segemet(x,y,0,ry,0,segl);
// segemet(0,segl,rx,ry,segl,0); // from -1 to 1


//
 strokeWeight(15-5*ry);
segemet(x,y,rx,-ry,segl,0);
 strokeWeight(12-3*ry);
segemet(segl,0,r,0,segl-50*ry,0);
 popMatrix();
  room();



}

void segemet(float x,float y,float rx,float ry,float w,float s) {

 //  strokeWeight(15);
  translate(x,y);
//  rotateX(ry*-PI/2);
//rotateZ(rx*-PI/2);
 //stroke(0, ry*10);
rotateY(-ry);
rotateZ(-rx);

  line(0,0,w,s);
}

void room()
{
```

```
 strokeWeight(.7);
  camera( w/2, h/2  , wall/1.1, // eyeX, eyeY, eyeZ
      w/2.0, h/2.0 ,0.0, // centerX, centerY, centerZ
     0.0, 1.0, 0.0); // upX, upY, upZ

 // ground
  pushMatrix();
  translate(w/2.0 ,h/2.0 + wall/2.0);
rotateX(radians(90));
fill(i);
  rectMode(CENTER);
  rect(0,0,llaw,wall);
  popMatrix();


  // roof
  pushMatrix();
  translate(w/2.0 ,h/2.0 - wall/2.0);
rotateX(radians(90));
  rectMode(CENTER);
  rect(0,0,llaw,wall);
  popMatrix();

 // left
    pushMatrix();
  translate(w/2.0 - llaw/2.0 ,h/2.0);
rotateY(radians(90));
  rectMode(CENTER);
 // fill(o);
  rect(0,0,llaw,wall);
  popMatrix();
// right
     pushMatrix();
  translate(w/2.0 + llaw/2.0 ,h/2.0);
rotateY(radians(90));
  rectMode(CENTER);
  rect(0,0,llaw,wall);
  popMatrix();

  //front
   pushMatrix();
  translate(w/2.0,h/2.0,-wall/2.0);
```

```
//rotateX(radians(90));
  rectMode(CENTER);
//  fill(m);
  rect(0,0,llaw,wall);
  popMatrix();
// x++;



}
```

Appendix III: Datasheets