

**INCORPORATING BIOLOGICAL SIGNALS  
FOR UNDERSTANDING USER  
INTENTIONS FOR INTELLIGENT  
WHEELCHAIR**

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198073V

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the Degree Master of Philosophy in Electrical Engineering

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## DECLARATION

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I declare that this is my own work and this thesis does not incorporate without acknowledgment any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgment is made in the text.

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## Abstract

Over the years Intelligent wheelchairs which can gather information from the environment to make decisions for itself have been developed to fulfil the needs of the wheelchair users. To improve the human robot interaction between the wheelchairs and the users, wheelchairs come with several types of controllers which are designed to meet the customer satisfaction. Use of biological/ electrophysiological signals for improved user satisfaction has an increasing demand all over the world.

In order to incorporate user intentions for the navigation purposes and object manipulation purposes of an intelligent wheelchair electrophysiological signals can be used. Due to the high signal to noise ratio and the fact that it does not require invasive surgical procedures to extract the electrophysiological signal, electromyography is used for above mentioned purposes. Since, electromyography is generated due to the motion intention of the user, it can accurately represent the intention of the user. Furthermore, the number of working muscles required to build a controller for above mentioned purposes is high. Hence, it can be seen that most of the existing electromyography based controllers use muscles associated with hand movements as they can generate several number of combinations of muscle activations depending on the hand movement/ grasping pattern. However, these are invalidated if the wheelchair user is suffering from physical conditions like trans-radial amputation where the upper limb is amputated between wrist and the elbow, trans-humeral amputation where the upper limb is amputated between shoulder and elbow and the partial/complete paralysis of the upper limb. This thesis proposes an Electromyography based controller for navigation and intelligent object manipulation of the wheelchair, which can be used even by the wheelchair users with trans-radial amputation, trans-humeral amputation and partial limb function. Any wheelchair user who has partial/complete function of biceps brachii of both of the arms, triceps brachii of the dominant arm and the right and left sternocleidomastoid of the neck, can use the proposed electromyography based controller. Moreover, the controller is enhanced with vision sensor and a proximity sensor for the intelligent object manipulation task. By using the common user preferences and his previous experience in arranging objects on a wheelchair tray controller was designed to be user friendly.

Experiments were carried out to monitor the adaptability and usability of the proposed Electromyography based controller among different users. Results confirmed that it can be used by any user after calibrating it for few trials. A human study was performed for different subjects to monitor whether patterns emerge in placing objects in different situations. After implementing a clustering algorithm, common locations and arrangements for object placements were identified. Furthermore, experiments were performed after building the whole system inside the CoppeliaSim simulation environment, to monitor the capability of the proposed system in manipulating and arranging objects according to the user preferences in different situations. Simulation results proved that the proposed system can place the objects in accordance with the results of the human study.

**Keywords-** cHRI, Electromyography, Reach to grasp, Navigation, Intelligent object manipulation, Intelligent Wheelchair

## DEDICATION

---

*To my loving wife*

*who has been the bed of roses in this road of prickles.....*

*and*

*to my dearest family*

*who keeps lifting me up unconditionally*

*every time I fall down.....*



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---

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## LIST OF ABBREVIATIONS

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|             |                                    |
|-------------|------------------------------------|
| <b>IW</b>   | Intelligent Wheelchair             |
| <b>EMG</b>  | Electromyography                   |
| <b>EEG</b>  | Electroencephalography             |
| <b>ECoG</b> | Electrocorticography               |
| <b>EOG</b>  | Electrooculography                 |
| <b>PWM</b>  | Pulse Width Modulus                |
| <b>PC</b>   | Personal Computer                  |
| <b>Tab</b>  | Tablet                             |
| <b>URDF</b> | Universal Robot Description Format |
| <b>HITL</b> | Human in the Loop                  |

## INTRODUCTION

---

People become wheelchair users for different reasons. Some of them has to go through this situation unexpectedly turning their life styles drastically [1, 2]. Wheelchair users often suffer from mental agony due to the fact that they have to be dependent of an external care giver all the time [3, 4]. Intelligent wheelchairs (IWs) which can gather information from the environment and make decisions for the wheelchair users, have been developed to enable the wheelchair users to be self-reliant [5, 6].

Intelligent wheelchair users often face troubles due to the failures of the input modalities occurred due to the external environment factors. For example, a widely used modality like voice commands tend to fail in a noisy environment. Hence, need of a modality that can get the user intentions without getting affected by such factors is arisen.

Biological signals can bring the user intentions with high accuracy. However, some of the biological signal extraction methods require invasive surgical procedures. Hence, those types of biological signal extraction methods are less preferred by the wheelchair as they may have already undergone several surgeries. Non invasive biological signal extraction methods are famous among the intelligent wheelchair users. Most commonly used biological signal/electrophysiological signal type is the surface Electromyography.

Because of the facts that surface Electromyography does not require any surgical procedures and the it has higher signal to noise ratio than of the other elec-



trophysiological signals it is preferred by the most of the intelligent wheelchair researches. Fast response to the intentions of the user, makes it highly reliable modality.

Even with the advancements of the science and technology, wheelchair user's needs have not been met for the fullest. Object manipulation is one of those areas that has not been addressed by the researches to the satisfaction of the wheelchair users. Object manipulation is not just about picking and placing the objects when consider about the user comfort and the satisfaction. It has to consider the user preferences above all.

Use of Electromyography for the navigation is a challenging task as it requires muscles which can provide measurable electrical potential to extract the muscle signals. With their physical disabilities considerable number of muscles cannot provide these muscle signals. Hence, the controlling algorithms will have to leverage the remaining limited number of muscles for electrophysiological signal extraction to achieve the navigation tasks according to the user intentions.

## **1.1 Motivation**

It is apparent that the limitations in extracting the muscle signals can limit the functionalities of the controlling algorithm as well. Hence, the wheelchair users who do not have the hand functions are severely affected by the lack of dexterity of the existing controllers. Most of the existing controllers like joysticks, hand gestures based controllers and even the electromyography based controllers which employs the signal generated in hand functions, rely on having a healthy hand to achieve the tasks.

Due to this fact, wheelchair users who suffer from trans-radial amputations, trans-humeral amputations and partial limb functions cannot use these wheelchairs and end up getting stressed over it. Hence, developing a controller which can be

used by these types of wheelchair users, has inspired this research and it could be a step towards building wheelchairs which can be used by any type of wheelchair user, in the future.

## **1.2 Contributions of the Thesis**

The research work presented in this thesis is towards the understanding of user intentions for intelligent wheelchair. The major contributions this thesis are outlined below.

- Propose an EMG based algorithm for navigation of a wheelchair
- Propose an EMG based algorithm for identifying the intention for using a robotic manipulator for reach to grasp task.
- Propose an intelligent object manipulation algorithm aided with combination of vision and EMG for wheelchair user
- Implementation and validation of the proposed system in CoppeliaSim Simulation environment.

## **1.3 Thesis Overview**

The thesis consists of five chapters. Organization of the thesis is as follows. Chapter 2 covers the literature review. Chapter 3 describes the EMG based controller proposed for navigation and intention detection of the user for the reach to grasp task and the human study performed for gathering the data for the object manipulation. Chapter 4 proposes and explains the intelligent object manipulation algorithm which uses the user's past experience and the EMG of the user. Moreover, it describes the implementation of the whole system inside

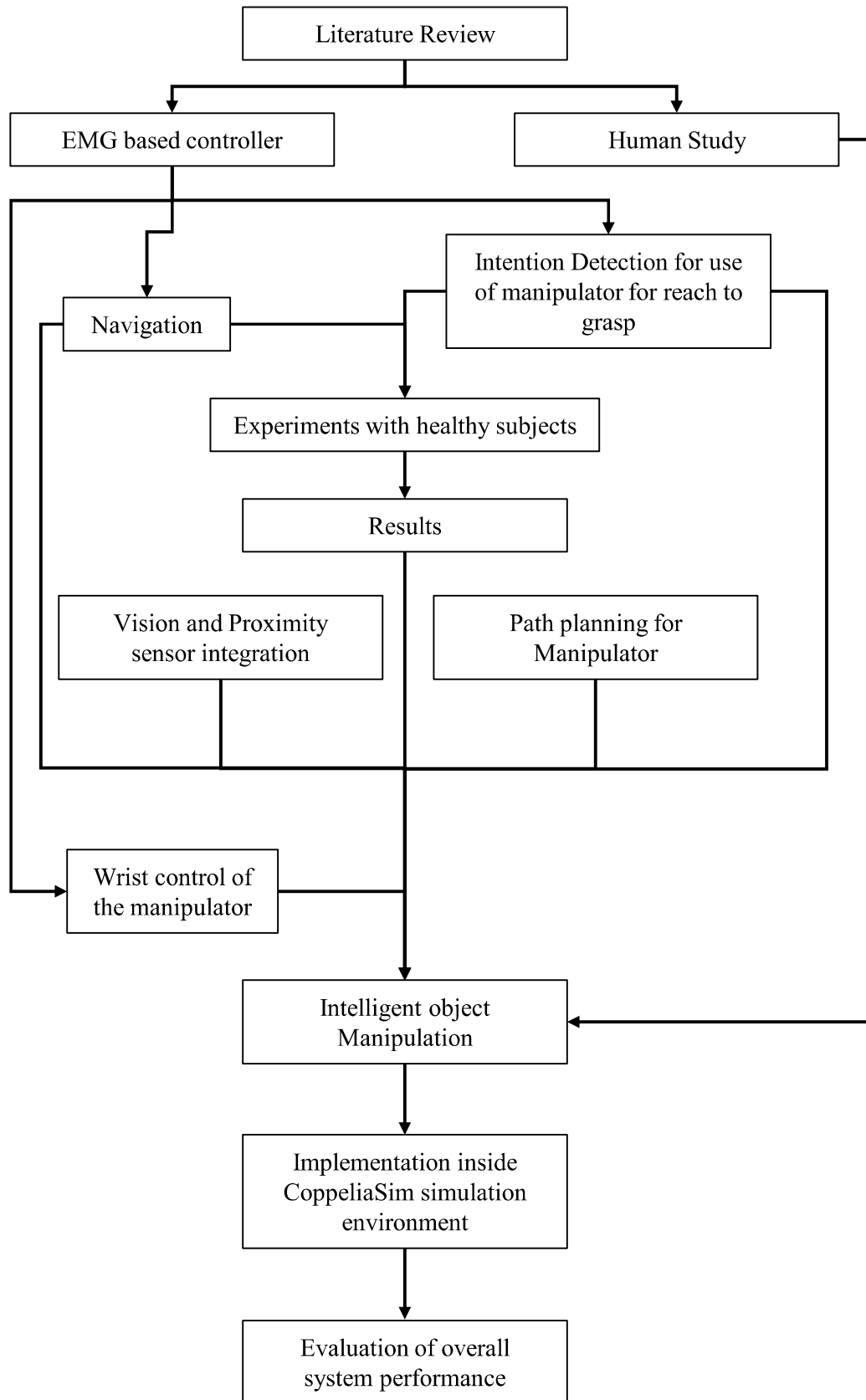


Figure 1.1: Overview of the research work

the CoppeliaSim simulation environment. Chapter 5 concludes the thesis with future directions.

The contents of the following chapters are elaborated below.

## **Chapter 2:- Literature Review**

This chapter covers the evolution of the wheelchairs, controlling algorithms used in existing wheelchairs, human factors to be considered with intelligent wheelchairs and the object manipulation associated with the intelligent wheelchairs.

## **Chapter 3:- Intelligent Wheelchair Controller**

Proposed EMG based controller and the performed human study is elaborated in this chapter. EMG based controller described here only considers about the navigation and the intention detection of the wheelchair user for reach to grasp motion. Human study performed to collect the data regarding the placing locations of the objects on the wheelchair tray is elaborated vividly in this chapter. Experimental results for both of these scenarios are also detailed in this chapter too.

## **Chapter 4:- Simulations and Results**

This chapter presents a detailed description of the implementation of the proposed controller improved to achieve the navigation and the intelligent object manipulation in simulation environment. Achieved object placing patterns for different tasks are discussed as the simulation results obtained from the implementation.

## **Chapter 5:- Conclusion**

This chapter concludes the thesis with future directions.

## LITERATURE REVIEW

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The concept of the Intelligent Wheelchair has a history over 4 decades. Over the years the functionality of these wheelchairs improved to assist the user in different ways. This chapter discuss about the evolution of the intelligent wheelchairs, controlling aspects associated with the wheelchairs, human factors that should be considered with the intelligent wheelchairs and the object manipulation for wheelcahir users.

### 2.1 Evolution of Intelligent Wheelchairs

Intelligent wheelchair is a wheelchair which has the ability to make decisions of its own according to the information gathered from the surrounding. The concept of intelligent wheelchair dates back to early 1950s where a Canadian inventor George Klein revolutionized the concept of a wheelchair with his invention: “The Klein Chair” [7] [see Figure 2.1]. It was developed as a assistance for quadriplegia patients caused by the second world war. Even though this wheelchair pioneered the intelligent wheelchair concept, the first successful intelligent wheelchair emerges in early 1980s.

In early 1980s, Stanford University developed a electrically powered wheelchair which uses the feedback of ultrasonic sensors for the obstacle avoidance for safe maneuvering of the wheelchair [12].

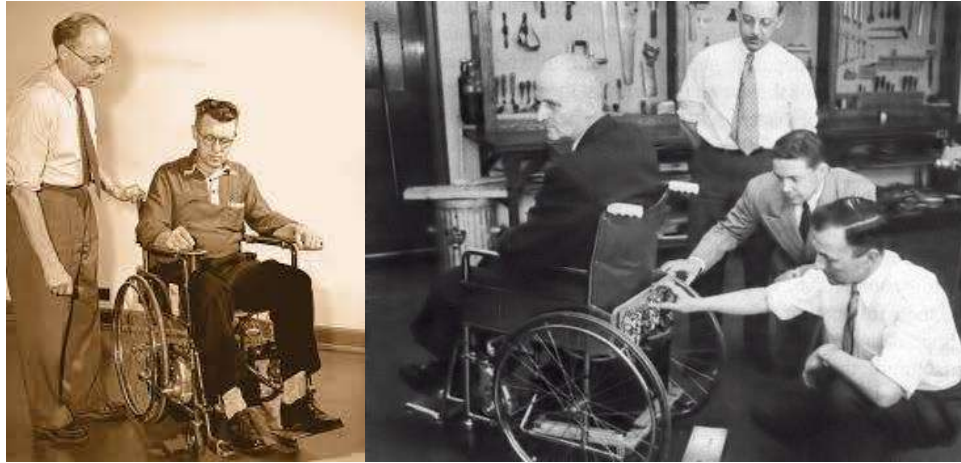


Figure 2.1: The Klein Chair developed in early 1950s [8]

Tin Man wheelchair project can be considered as a turning point of the Intelligent Wheelchair development. This project was initiated to develop autonomous wheelchairs for an affordable price for the society [9, 13–15]. Tin Man I [see Fig. 2.2(a)] was run extensively over a limited set of indoor environments. The environments were prepared in that hazards which were known to be beyond the capabilities of the robot had been removed. With 12 infrared sensors, sonar sensors, wheel encoders and several pressure switches on a front bumper Tin Man II [see Fig. 2.2(b)] was able to navigate autonomously while avoiding obstacles. Many of the problems mooted in Tin Man I were successfully eliminated by Tin Man II.



(a)



(b)

Figure 2.2: Tin Man Wheelchairs [9]: (a) Tin Man I (b) Tin Man II



Figure 2.3: Wheelesley developed in 1995 [10]

In 1995 a successful wheelchair named “Wheelesley” [see Fig. 2.3] was developed by the researches of Wellesley College, Massachusetts [17]. With an autonomous navigation system, Wheelesley consisted of a Graphical User Interface (GUI) [see Fig 2.4] to control the wheelchair effectively. In the later part of 1995 TAO project was initiated by Applied AI Systems, Inc. (AAI). The project was carried out in Canada and Japan simultaneously. TAO-1 [see Fig. 2.5] was developed targeting the disabled population of Canada [18]. Through computerized

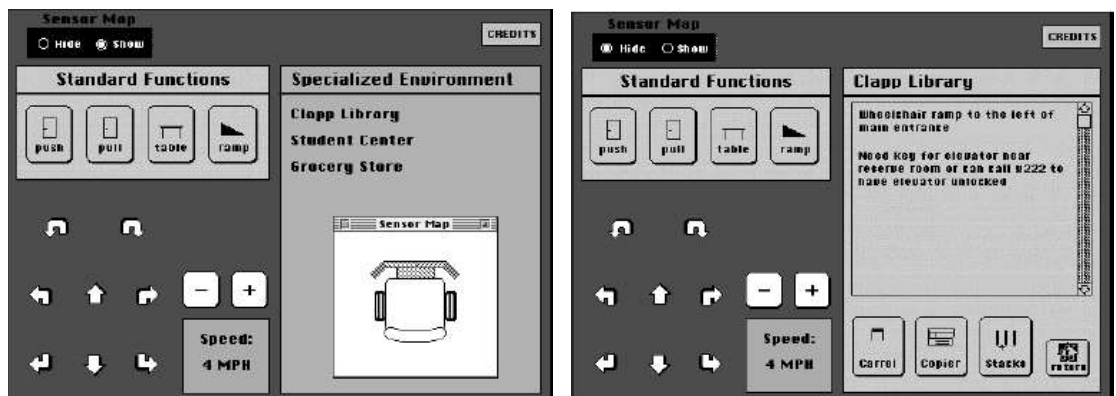


Figure 2.4: GUI of Wheelesley wheelchair [10]



Figure 2.5: Prototype of TAO-1 [11]

autonomy management unit and a set of sensors (on-board CCD cameras and infrared (IR) sensors), TAO-1 can avoid both stationary and moving obstacles.



Figure 2.6: Prototype of TAO-2 [11]



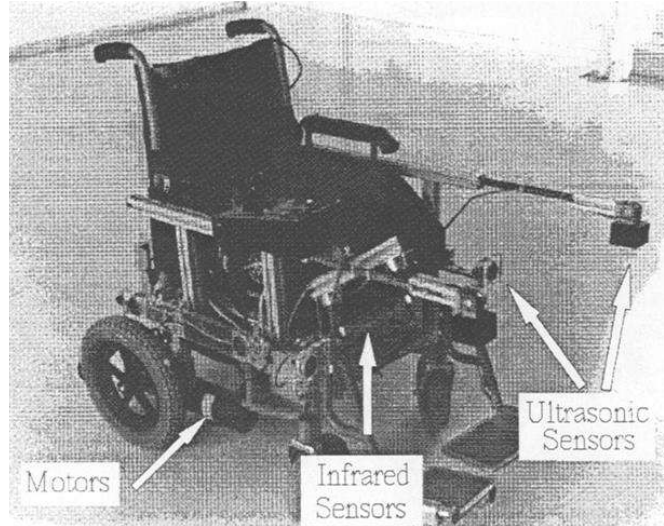


Figure 2.7: UMIDAM wheelchair developed in 1995 [16]

With the availability of that function, TAO-1 was able to perform tasks such as passage through a narrow corridor, entry through a narrow doorway and maneuver in a tight corner. TAO-2 [see Fig. 2.6] was developed in Japan to eliminate the problems encountered in TAO-1 prototype. The over-all computer hardware, software structures and sensors are almost identical to those for TAO-1, except for a few changes to accommodate the above mentioned functions.

In the same year, UMIDAM project developed a wheelchair to address the problems which were failed to address by the wheelchairs of that time [19]. The developed wheelchair [see Fig. 2.7] was capable of autonomous navigation and avoiding obstacles through a controller consisted of a dependent-user recognition voice system and ultrasonic and infrared sensor systems.

In 1999, another intelligent wheelchair: NavChair was developed [20]. This was developed using commercially available and electrically powered wheelchair. The obstacle avoidance routines used by the NavChair [see Fig. 2.8] in conjunction with the ultrasonic sensors were modifications of methods originally used in mobile robotics research. With that navigation system, it can operate in three modes to avoid obstacles and to follow the walls to navigate to the desired position.



Figure 2.8: NavChair developed in 1999 [9]

In 2000, the SIAMO project [17] was able to develop the UMIDAM wheelchair [16] to a new level with an innovative user-machine interface, a complete sensory subsystem , and an advanced strategy of control and navigation [see Fig. 2.9]. Sensory subsystem consisted of sensors such as ultrasonic, infrared, vision, etc and biological signal capturing electrodes such as electro-oculographic electrodes.

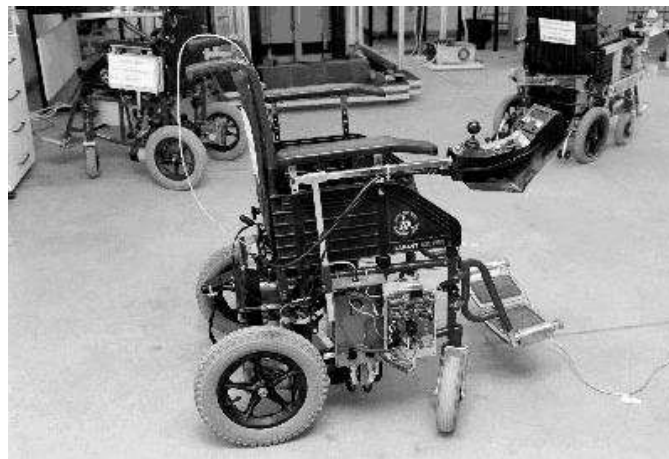


Figure 2.9: SIAMO wheelchair prototypes in 2000 [21]

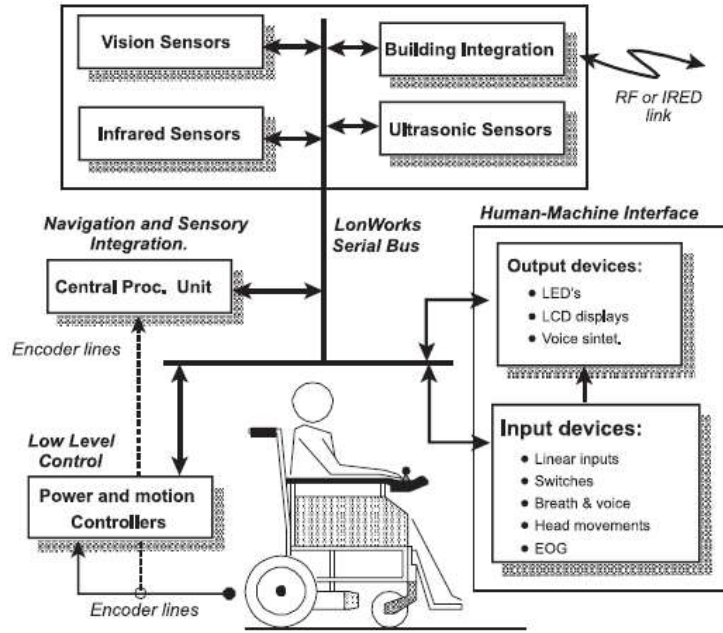


Figure 2.10: Functional blocks of the whole system of SIAMO wheelchair prototype [21]

In 2008, INTELLWHEELS intelligent wheelchair project developed a prototype of INTELLWHEELS [23]. Developed prototype [see Fig. 2.11] was controlled through a multi modal interface (voice, head movements, joystick, keypad



Figure 2.11: INTELLWHEELS wheelchair prototype developed in 2008 [22]



Figure 2.12: VAHM-3 wheelchair prototype with a deictic interface developed in 2010 [25]

and simple facial expressions) in order to achieve semi- autonomous/autonomous navigation. In 2010, VAHM project improved the existing VAHM-3 prototype by incorporating deictic approach to the wheelchair [24]. With the improved Human machine interface and Human machine interaction [see Fig. 2.12], it enabled the ability to pass through narrow passages and wall following for the wheelchair.

In 2013, RoboChair Intelligent Wheelchair was developed Unitec Institute of



Figure 2.13: RoboChair Intelligent wheelchair developed in 2013 [26]

Technology, New Zealand [27]. Robochair [see Fig 2.13] consisted of features such as voice, vital signs (blood pressure, blood oxygen saturation, body weight, and bio impedance), cardiovascular risk prediction communicating and provide companionship through multi-modal interactions. With highlighting features like low cost, simple user interface, simple operation, voice controlled navigation, robustness and open-source software interface RoboChair was designed to act as a social companion.

ATEKS platform for intelligent wheelchairs [see Fig. 2.14] was developed in year 2014 [29]. With a Kinect incorporated to the wheelchair, ATEKS was targeted to develop a high level controller for the wheelchair platforms. Apart from the Kinect sensor ultrasonic sensors were added to the wheelchair for the autonomous navigation of the wheelchair.

Action Trackchair project was initiated in 2009 to develop powered wheelchairs to navigate on uneven terrains autonomously. In 2015, Action Trackchair was made commercially available for the users with several modes of user configurations on the wheelchair (i.e. standing and sitting) [30]. [see Fig. 2.16]. Apart



Figure 2.14: ATEKS wheelchair platform developed in 2014 [28]



Figure 2.15: iChair developed in 2015 [33]

from the joystick control for the high level control of the wheelchair, a Brain Computer Interface is used for the high level control of the wheelchair.

Intelligent powerchair (iChair) [see Fig. 2.15] was developed by University of Nevada, Reno in 2015 [33]. Autonomous navigation and the obstacle avoidance were incorporated for the wheelchair through the information gathered from the camera feedback and the proximity sensor data. Moreover, this wheelchair had a tray to keep personal laptop while enabling the mouse control through trackers placed on the forehead. With two robotic arm attached to the wheelchair it had the capability to handle the objects for the user. Interaction of the user was done through the personal laptop of the wheelchair.



Figure 2.16: Action Trackchair developed in 2015 [30]



Table 2.1: Literature survey results of Garcia *et al.* in 2013 [31]

| <b>Concept</b>         | <b>From<br/>1980</b> | <b>From<br/>1985</b> | <b>From<br/>1990</b> | <b>From<br/>1995</b> | <b>From<br/>2000</b> | <b>From<br/>2005</b> | <b>From<br/>2010</b> | <b>Actual<br/>2010-2013</b> |
|------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|-----------------------------|
| Advanced Wheelchair    | 1                    | 3                    | 8                    | 26                   | 24                   | 68                   | 81                   | 57                          |
| Autonomous Wheelchair  | 0                    | 2                    | 11                   | 95                   | 189                  | 322                  | 356                  | 249                         |
| Intelligent Wheelchair | 0                    | 3                    | 11                   | 104                  | 182                  | 541                  | 899                  | 629                         |
| Robotic Wheelchair     | 0                    | 0                    | 3                    | 72                   | 237                  | 749                  | 901                  | 631                         |
| Smart Wheelchair       | 3                    | 4                    | 13                   | 59                   | 80                   | 391                  | 544                  | 381                         |
| Totals                 | 4                    | 12                   | 46                   | 356                  | 712                  | 2071                 | 2781                 |                             |
| Relative Increments    |                      | 200%                 | 283%                 | 674%                 | 100%                 | 191%                 | 34%                  |                             |

Table 2.2: Literature survey results of Leaman and La in 2017 [32]

| Keywords                       | Google Scholar | IEEE Xplore |
|--------------------------------|----------------|-------------|
| Powered Wheelchair             | 17500          | 487         |
| Electric Wheelchair            | 16900          | 367         |
| "Powered Wheelchair"           | 4450           | 140         |
| "Electric Wheelchair"          | 5260           | 160         |
| "Intelligent Wheelchair"       | 2480           | 131         |
| "Autonomous Wheelchair"        | 952            | 35          |
| "Robotic Wheelchair"           | 2300           | 131         |
| "Human Factors" + "wheelchair" | 715            | 1           |

In 2016, University of Ljubljana, Slovenia developed a wheelchair [see Fig. 2.17] which can travel on any kind of terrains such as curbs, ramps, and stairs [34]. Autonomous stair climbing and obstacle avoidance too were available with this wheelchair.

There are numerous number of wheelchairs can be found in the literature under the theme intelligent wheelchair. In 2013, Garcia *et al.* [31] conducted a survey on the available literature based on the search engine: Google Scholar. It reveals the



Figure 2.17: All Terrain-Wheelchair of University of Ljubljana, Slovenia developed in 2016 [34]



fact that the researches on intelligent wheelchairs are increasing at an exponential rate [see Table 2.1]. In 2017, Leaman and La published a review on the past, present and future of intelligent wheelchairs [32]. According to that, the number of the researches which can be found through search engines: Google Scholar and IEEE Xplore has increased to a huge number [see Table 2.2] compared to the findings of Garcia *et al.*

## **2.2 Controlling Wheelchairs**

Developing a controller for an wheelchair is a sophisticated task as it is required to consider so many aspects before and after designing it. This section looks deep in to the such aspects and summarises what has done in the literature so far with regards to the controlling of the wheelchairs.

### **2.2.1 Control Inputs/ Input Modalities for Wheelchairs**

Wheelchairs need control inputs for achieving vast range of tasks. In order to perform from a basic task like moving the wheelchair to a complex task such as understanding the user behavior, a wheelchair gathers information from the surrounding through the control inputs. Those information will be used to make the decisions of the wheelchair controlling algorithm to perform the desired tasks [35].

There are several kinds of control inputs that can be found in the literature. Some of the control inputs are generated by means of mechanical actuation (eg. Joysticks). Control inputs which are gathered from the sensors attached to the wheelchair and the wheelchair user has become the most popular method for decision making of wheelchair.

From “The Klein Chair” the to a modern day wheelchair, control inputs generated from joystick controller has been a popular method among the researchers all around the globe [36]. In the early researches, the joysticks consisted of simple lever mechanisms which were used as basic on off switches to control the forward and backward motions of the wheelchair [37]. Gradually, these joysticks were improved to become controllers which could control the wheelchair proportionally to the lever movements of the joysticks. As the researches progress with time, researches were tempted to seek other possible scenarios for the joysticks. At first researches moved on to the joysticks controlled by chin movement of the user. A

knob made as the shape of the chin was attached to the lever of the joystick in order to control the joystick and was placed at the chin level of the wheelchair user [38, 39].

However, this method was not suited for the prolonged use of the wheelchair. Hence, researches were shifted to make joysticks with sip and puff control. In this method, air was sucked (sip) or blown (puff) by the wheelchair user through a straw coupled to pneumatic switches to control the wheelchair. According to the speed and volume of the air flowing in side the straw, this control method has been developed to a state where the wheelchair user can control the speed and direction of the wheelchair [40–42].

With the improvements in the concepts of the intelligent wheelchair, researches sought to improve the human robot interaction (HRI). HRI can be divided in to two main categories: physical human robot interaction (PHRI) and cognitive human robot interaction (CHRI) (More details of HRI will be discussed under the sub section 2.3.1). In this regard, researches were carried out to incorporate touch pads to the intelligent wheelchairs. This research acquired successful results over the years for some paraplegic patients. However, quadriplegic patients found it to be unusable [43–45].

Large scale body movements based wheelchair control methods have acquired promising results during the last two decades. Movements of head [39, 46–48], arms and torso [49] comes under the above mentioned movements. Tracking those movements has been done using cameras and sensors like leap motion sensors and Kinect sensors. This method became useful for quadriplegic patients too. Hence, there are numerous researches can be found in the literature in this regard. Moreover, body movement across a defined neutral place/ position/ plane is tracked and is calibrated according to the desired function of the wheelchair controller.

Hand gesture is another modality that was influenced from the previous modal-

ity: large scale body movement. In Activities of Daily Living, humans use various hand gestures to express their intentions and emotions. In order to achieve the motion of wheelchairs, using the gestures which depict the directional intentions (deictic gestures) is the most common approach used in the literature. Since these gestures contain both directional commands and the user intentions, hand gesture based wheelchair controllers have improved the HRI [25, 50, 51]. In the recent past, Rabhi et al. [52] developed a virtual joystick which can classify the gestures of the healthy hand gestures as well as the gestures of dystonia patients.

Using electrical switches is another method for giving inputs to control the intelligent wheelchairs. However, this method was used in early versions of the intelligent wheelchairs. In order to achieve the required function, electrical switches were available for each function. Switches were operated by means of a healthy body part (foot, hands, chin and etc.) [53, 54]. With the growth of the concept of intelligent wheelchair this control became obsolete in the sense of the control inputs available in the present context.

Gaze detection is another modality that is widely used event at the present contexts of the control inputs [55–58]. However, the researches on gaze detection has a history which runs back 1879. Eye tracking systems can be categorized into several categories. The are wearable [59, 60] / non-wearable [61, 62] and infrared-based [63–65]/ appearance-based eye tracking systems [66, 67]. In infrared-based systems, shining light on the subject creates a “red-eye effect:” the difference in reflection between the cornea and the pupil is used to determine the direction of sight. In appearance- based systems, computer vision techniques are used to find the eyes in the image and then will determine their orientation. Wearable systems are the most accurate and also the most intrusive. Infrared systems are more accurate than appearance- based, but there are concerns over the safety of prolonged exposure to infrared lights. Appearance-based systems use both eyes to predict gaze direction. Therefore the resolution of the image of each eye is often small hence less accurate. The main issues in developing gaze tracking

systems are intrusiveness, speed, robustness, and accuracy [68]. Gaze analysis can be performed at three different levels: highly detailed low-level micro-events, low-level intentional events, and coarse-level goal-based events [69]. Micro-events include micro saccades, jitter, nystagmus, and brief fixations.

Using voice input can be considered as the most commonly used and most popular control input among the wheelchair user. Voice is the most convenient way for user to express his/her intentions. Thus, it has become the most preferred modality among the intelligent wheelchair researches [70–76]. With the micro-controllers, amplifiers and the high tech mikes it has become a relatively easy task to bring the voice input to the digital domain. However, the major drawback of this method is that it is difficult to extract the voice input information if the noise of the surrounding is too high. Hence, the need of another modality which can be used to express the wheelchair user’s intentions while being convenient to user is arisen. Use of biological signals as an input modality for the intelligent wheelchairs was emerged as a remedy for this matter. Sub section 2.2.1: “Biological Signals” illustrates the usability of biological signals in intelligent wheelchairs comprehensively.

Recent advances in the control of intelligent wheelchairs based on biological/electrophysiological signals can meet the needs of patients who are suffering from diseases like hemiplegia, quadriplegia, spinal cord injuries, Parkinson’s disease or muscular dystrophy [77]. Most of the above mentioned modalities tend to fail if a person is suffering from these conditions. There are three types of non-invasive biological signals can be found in the literature. They are electromyography (EMG), electroencephalography (EEG) and electrooculography (EOG). Moreover, there are invasive methods of biological signal extraction methods like electrocorticography (ECoG) and intra-muscular electromyography can be found in the literature too. However, it can be seen that the available literature on intelligent wheelchairs which use the biological signals as its input modality, have not used the invasive biological signal monitoring methods. Main reason that

can be considered in this regard is that the reluctance of the wheelchair users to under go a surgery to implant those electrodes because they may have already undergone one or more surgeries due to their reason for using wheelchair.

### Control Inputs - Biological Signals - *EMG*

EMG tracks the electrical potential generated on muscles due to the motion intentions. Motion intentions are generated in the brain and are transferred to the muscles through the neurons. Then the relevant muscles are activated and an electrical potential is generated on the surface of the muscle. There are two types of EMG signals: surface EMG (sEMG) [78] and intra- muscular EMG. sEMG tracks the EMG through electrodes attached to the surface of the body. In this method, EMG signals generated in the muscles which are located deep inside the body (muscles which are not in contact with the human skin), cannot be tracked. In order to track these signals, an electrode is surgically placed on the surface of the relevant muscle. This method is called intra- muscular EMG [79]. However, this method is not preferred by the majority of the wheelchair users due to its surgical procedure. Hence, the use of intra- muscular EMG as a modality to control the wheelchair is rarely found in the literature.

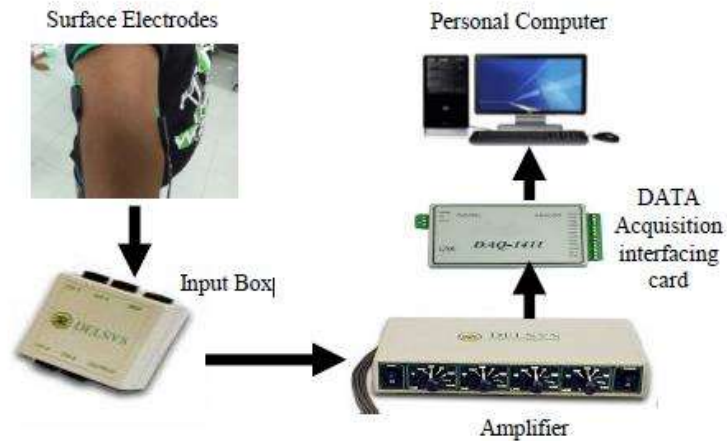


Figure 2.18: Delsys Bagnoli 16 channel EMG acquisition system

In order to acquire EMG data for controlling a intelligent wheelchair an EMG acquisition system is required. A basic EMG acquisition system consists of 3 major components: EMG electrodes, an amplifier and a personal computer [see Fig.2.18]. Through an EMG acquisition system raw EMG data is brought in to the personal computer. the usable energy of EMG signals is limited to a frequency range of 0 to 500 Hz. These raw data are the filtered for and processed for the feature extraction. There are several features which are commonly used in intelligent wheelchair controlling, can be found in the literature. According to [80], they are Mean absolute value, Integral absolute value, Root mean square, Variance of EMG, Waveform length, Zero crossing, Slope sign change, Median frequency, Mean frequency and Linear prediction coefficients [see Fig. 2.19]. For

| Feature extraction                                       | Definition                                                                                                                                                                                          |
|----------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mean absolute value (MAV), Integral absolute value (IAV) | $MAV \text{ or } IAV = \frac{1}{N} \sum_{n=1}^N  x_n $                                                                                                                                              |
| Root mean square (RMS)                                   | $RMS = \sqrt{\frac{1}{N} \sum_{n=1}^N x_n^2}$                                                                                                                                                       |
| Variance of EMG (VAR)                                    | $VAR = \frac{1}{N-1} \sum_{n=1}^N x_n^2$                                                                                                                                                            |
| Waveform length (WL)                                     | $WL = \sum_{n=1}^{N-1}  x_{n+1} - x_n $                                                                                                                                                             |
| Zero crossing (ZC)                                       | $ZC = \sum_{n=1}^{N-1} [\text{sgn}(x_n \times x_{n+1}) \cap  x_n - x_{n+1}  \geq \text{threshold}]$ ;<br>$\text{sgn}(x) = \begin{cases} 1, & \text{if } x < 0 \\ 0, & \text{otherwise} \end{cases}$ |
| Slope sign change (SSC)                                  | $SSC = \sum_{n=2}^{N-1} [f[(x_n - x_{n-1}) \times (x_n - x_{n+1})]]$ ;<br>$f(x) = \begin{cases} 1, & \text{if } x \geq \text{threshold} \\ 0, & \text{otherwise} \end{cases}$                       |
| Median frequency (MDF)                                   | $\sum_{j=1}^{MDF} P_j = \sum_{j=MDF}^M P_j = \frac{1}{2} \sum_{j=1}^M P_j$                                                                                                                          |
| Mean frequency (MNF)                                     | $MNF = \frac{\sum_{j=1}^M f_j P_j}{\sum_{j=1}^M P_j}$                                                                                                                                               |
| Frequency ratio (FR)                                     | $FR = \frac{P(f_1)}{P(f_2)}, f_1 \ll MNF \ll f_2$                                                                                                                                                   |
| Linear prediction coefficients (LPC)                     | $\hat{x}_n = \sum_{i=1}^p a_i x_{n-i}$                                                                                                                                                              |

Let  $x_n$  represents the EMG signal in a segment.  $N$  denotes the length of the signal.  $P_j$  is the EMG power spectrum at frequency bin  $j$ .  $f_j$  is the frequency of the spectrum at frequency bin  $j$ .  $a_i$  is linear predictive coefficients.  $\hat{x}_n$  is the predicted signal value.

Figure 2.19: Mathematical definition of feature extractions used for EMG signal pattern recognition method [80]

the processing of the EMG data mainly two types of methods are used: non-pattern recognition method and pattern recognition method [81]. Non-pattern recognition method is focused on the threshold or onset analysis method. Hence the command inputs which can be generated from this method are limited. In contrast to this method, pattern recognition-based EMG gives a vast range of control inputs by using the above mentioned features. For this purpose numerous classifiers are used. Artificial Neural Networks (ANN) are used to classify the EMG signal data. Various types of ANNs are available in the literature. In 2008, Wei et al. [82] proposed method as an advancement of the traditional ANNs where they used back propagation ANN (BPANN) with the Levenberg-Marquardt algorithm [83] to classify steady features from both the time domain and the frequency domain [see Fig. 2.20]. Several other BPANNs [see Fig. 2.21] which have been implemented to classify the EMG data to control the intelligent wheelchairs, can be found in the literature [84]. Moreover, implementation Conic section function neural networks [85, 86] and time-delayed artificial neural networks [87] to improve the accuracy of the classifications can be found in the recent researches.

The fuzzy approach and the neuro-fuzzy approach [80, 89] are another classification methods that has been successfully implemented on the EMG based classifiers to control the intelligent wheelchairs over the years. The advantage of fuzzy classification is that it is tolerant of imprecision when used in an EMG-based control utilizing a non-stationary signal. Implementation of fuzzy C-means algorithm and fuzzy min-max neural networks (FMMNN) can be found in the early literature in this regard [90, 91]. Later, researches proved that the FMNNN has better performance than the fuzzy C-means algorithm. Apart from those two method there are other neuro-fuzzy approaches such as fuzzy clustering neural networks [92], the adaptive neuro-fuzzy interference system [93], ANN and fuzzy inference systems [94], and fuzzy ARTMAP networks [95]. These studies all revealed that the classification performance of these approaches was much better than those of traditional ANNs and traditional fuzzy logic systems.



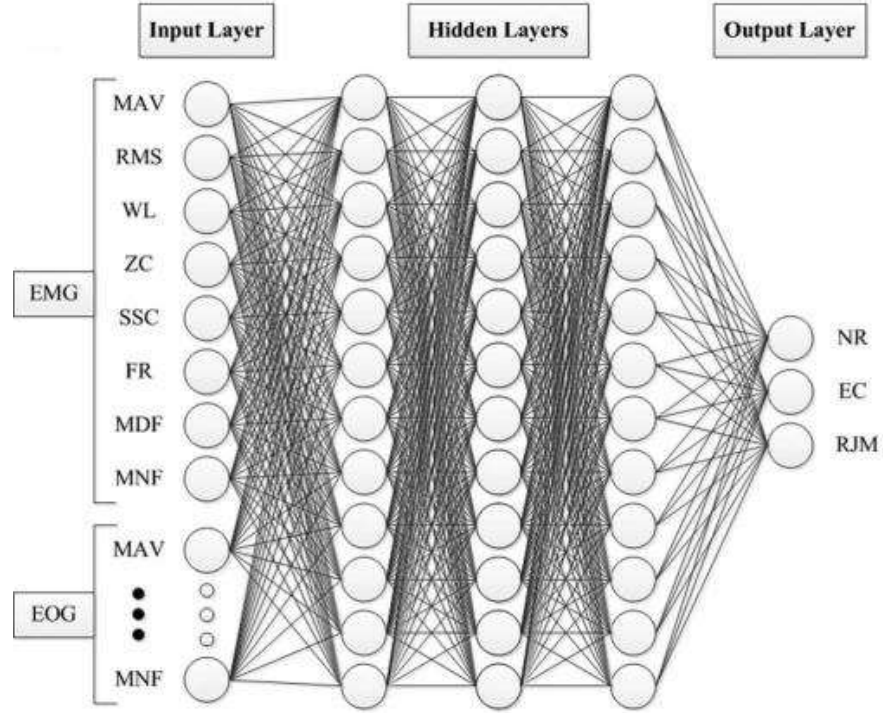


Figure 2.20: Schematic diagram of back propagation artificial neural networks with Levenberg-Marquardt algorithm [82]

Probabilistic approach is another pivotal classifier in terms of EMG based pattern recognition methods. There are few methods can be found in this regard in literature. Hidden Markov model (HMM) [96] and Gaussian mixture model (GMM) [97] have been used in the researches very often. HMM method can overcome problems with non-stationary feature estimation and can therefore be more effective than other classification methods. Both HMM and GMM have been suggested as ways of overcoming real time constraints in the control of the intelligent wheelchairs. Moreover, GMM has been improved to by the log-linearized Gaussian mixture network (LLGMN) method [98]. LLGMN is a classifier that is able to use raw EMG signals rather than EMG features. LLGMN has the useful property of being capable of online training which is essential in overcoming increasing errors during long-time control.

Another classification method that comes under the pattern recognition method is support vector machines (SVM). The SVM classifier also demonstrates an

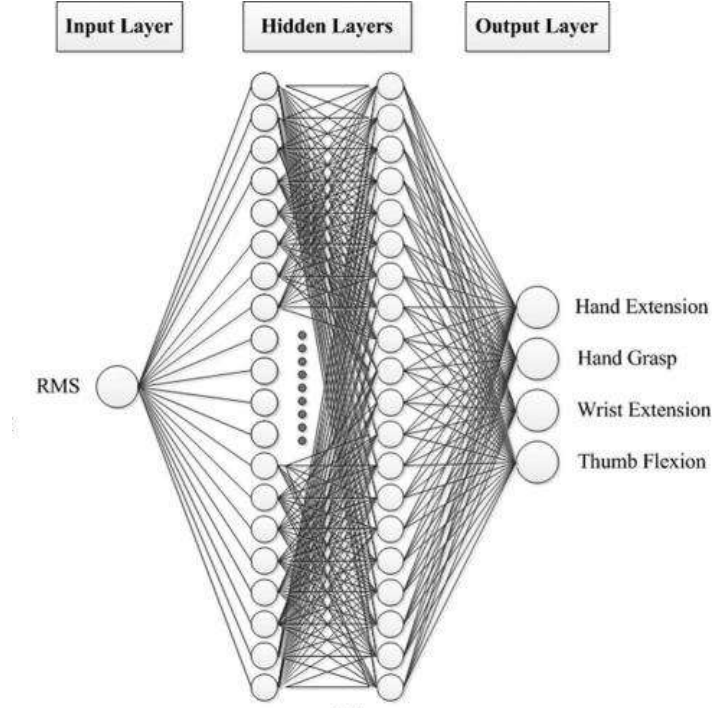


Figure 2.21: Schematic diagram of back propagation artificial neural networks with gradient descent algorithm [88]

exceptionally robust performance and a low computational load [99–101]. It has been experimentally evaluated and their classification performance has been found to be equal or better than other classifiers such as BPANN and linear discriminant analysis (LDA) [102].

Even though EMG has some attractive properties which are very useful in controlling an Intelligent Wheelchair, it requires muscle activation to generate the necessary EMG signal outputs. However, wheelchair users who are suffering from diseases like strokes and spinal cord injuries cannot generate the EMG signals because the path from brain to muscle is damaged by the disease. Hence, researches have moved on to the other biological signals like EOG and EEG.

## Control Inputs - Biological Signals - *EOG*

Electrooculogram is the signal produced as a result of eye ball movements and can be used to control mobility aids. Electrooculography (EOG) is a technique for measuring the corneo-retinal standing potential that exists between the front and the back of the human eye [103]. EOG signals are frequently varying and stuck between 50 to 3500  $\mu\text{V}$  with a frequency range in between 0 to 100 Hz [104,105]. Any regular change of the eye movement makes a difference in the direction of the positive and negative pulse to the dipole, can be measured.

For EOG signal tracking, electrodes are placed near to the human eye to record vertical and horizontal eye movements. Here electrode on the forehead acts as the ground [see Fig. 2.22]. There are six muscles which are responsible for controlling the activities of eye movements and eye positions. Those muscles are called extra-ocular muscles [106]. Function of the extra-ocular muscles are depicted in Table 2.3.

For the classification of the extracted EOG signals classification methods discussed in the previous section are also used for the classification of EOG signals. ANN, HMM, LDA, SVM and Fuzzy Logic approaches are commonly used methods for the classification of EOG signals. Apart from these methods there are other methods which have been used to classify the EOG signals. In 2007, Trikha et al.

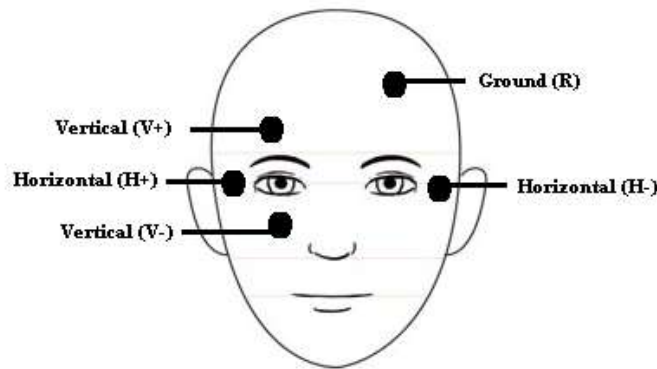


Figure 2.22: Electrode placement for EOG [106]

Table 2.3: Extra-ocular muscles activity [106]

| <b>Extra - Ocular Muscles</b> | <b>Activities perfomed by the muscles</b>                              |
|-------------------------------|------------------------------------------------------------------------|
| Medial Rectus (MR)            | Shift the eye inward and near to the nose                              |
| Lateral Rectus (LR)           | Moves the eye outward and away from the nose                           |
| Superior Rectus (SR)          | Moves the eye upward and top of the eye                                |
| Interior Rectus (IR)          | Revolve the eye downward and away from the nose                        |
| Seperior Oblique (SO)         | Turn around top of the eye near the nose and transfer eye outward      |
| Inferior Oblique (IO)         | Spin the top of the eye away from the nose, eye upward and eye outward |

developed a classifier for EOG signals based on the technique: Movement Classifier Deterministic Finite Automata (MCDFA) [107]. With the success obtained from this research this method has been used in many EOG related researches.

### **Control Inputs - Biological Signals - *EEG***

Several reasons have been discussed in the previous sections to prove that there is a need for biological signals to control the wheelchair. These led to the development of Brain Computer Interface (BCI) control wheelchair. EEG signals are voltage fluctuations due to activity in the neurons which may occur due to collaboration of different part of the brain in performing a task or due to different brain dynamics [108]. For the classification of the EEG signal, known behaviors of the brain are required. Commonly used method in this regard is the Event Related Synchronization (ERS). ERS occurs due to the suppression of  $\mu$  waves during the motor imagery [109].

P300 is a positive deflection in the EEG wave found due to visual or audio stimulus [118, 127, 128]. This phenomena occurs due to odd-ball paradigm where a positive deflection of signal is seen with a delay of usually 300ms after a target stimulus is presented [129]. Steady state visually evoked potentials (SSVEP) are signals that are response to visual stimuli shown at specific frequency usually a spike in power of the stimulus frequency is seen [120, 130].

Table 2.4: Feature extraction techniques [108]

| Signal Type                    | Mechanism to extract feature                                                                                                                                                                                                                                                                                                                                | Feature used                                                                                                                                                                                                                                                       |
|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ERD                            | <p>Band power of the EEG signal is calculated from 5 channel [110]</p> <p>Uses canonical variant analysis to extract stable frequency [111]</p> <p>Uses CSP(common spatial pattern) to extract the most discriminative feature [112]</p> <p>Uses Discrete wavelet transform to decompose into four principal frequency ranges of the brain waves. [113]</p> | <p>Band power of the EEG signal as feature [110]</p> <p>Power Spectral Density of the frequency [111]</p> <p>Common spatial pattern between left and the rest, right and the rest, feet and the rest [112]</p> <p>Energy of alpha, theta, gamma and beta [113]</p> |
| P300                           | <p>From the recorded EEG data, both for P300 and Non P300 average and standard deviation is calculated for each channel [114, 115]</p> <p>Identification of P300 signal by visual inspection</p>                                                                                                                                                            | <p>P300 target signal and Non-P300 target signal [114–119]</p>                                                                                                                                                                                                     |
| SSVEP                          | <p>Spectral density of EEG signal is calculated [120]</p>                                                                                                                                                                                                                                                                                                   | <p>Power of each stimulus frequency [120]</p>                                                                                                                                                                                                                      |
| Data value from Commercial BCI | -                                                                                                                                                                                                                                                                                                                                                           | <p>Blink, Attention ,Meditation Value [121–124]</p>                                                                                                                                                                                                                |
| Hybrid                         | <p>(SSVEP and P300) Power spectral Density of signal is calculated for SSVEP [125]</p> <p>(<math>\mu</math> and P300) Uses CSP(common spatial pattern) to extract the most discriminative feature [126]</p>                                                                                                                                                 | <p>P300 target signal and Non-P300 target signal also power of each stimulus frequency [125]</p> <p>CSP pattern between one versus rest for <math>\mu</math> and P300 signal [126]</p>                                                                             |

EEG signals acquisition is mainly done by placing electrodes on the scalp. 10-20 system is the most common standard used to place electrode. Unlike EMG signals, signal to noise ratio (SNR) of EEG is very high. Hence, a careful pre-processing is needed before the feature extraction process. CSP (common spatial pattern), PCA are also used to reduce signal to noise ratio. Threshold-based noise rejection and common average reference (CAR) of multiple electrodes is also used to reduce SNR. Visual inspection of signal and seeing if a signal contains interested signal are also used [108]. Apart from those methods, general signal filtering methods like band pass filtering and etc can be found in the literature.

Feature extraction in BCI application is the process of extracting feature that can be used to distinguish the EEG signal into different classes. Rahul et al. summarized the existing feature extraction methods and it is depicted in Table 2.4.

### **2.2.2 Operating Modes**

Operating intelligent wheelchairs can be done in several modes. Autonomous, semi - autonomous and manual are the principal operating modes that can be found in the literature. However, the decision to make the wheelchair to an autonomously operated intelligent wheelchair or to any other operating mode, depends on the capabilities of the wheelchair user. For example, if a patient has a walking impairment while having healthy upper body, a simple joystick controller would be suffice to fulfill his operations. Obstacle avoidance can be considered as the common factor for all types of operating modes [131, 132].

## **Machine Learning**

Specialized computer algorithms are required for intelligent wheelchairs to provide the artificial intelligence needed to make quick decisions about navigation and obstacle avoidance. Some examples of machine learning in intelligent

wheelchairs include the use of neural networks to detect obstacles and reproduce pretaught routes; some use obstacle density histograms to combine information from sonar sensors and joystick input from the user, while others use rule-based approaches. The LIASD intelligent wheelchair has a control architecture that uses the virtual impedance principle [133]. This approach ensures a smooth implementation of desired tasks by taking into account some real impedance parameter properties such as inertia, viscosity, and stiffness. Tyagi et al. [134] use fuzzy control, which allows the use of inexpensive and imprecise sensors, keeping the overall system cost and complexity low. Most of the intelligent wheelchairs use reactive control methods, like subsumptive architectures, as the lowest layer of a multi layer architecture . This layer interacts directly with the underlying hardware, while upper layers provide deliberative reasoning and control [36]. Tang et al. introduce a system that makes extensive use of freely available open-source software [135]. The Player Project has, as the base framework, GMapping for mapping, Vector Field Histograms for obstacle avoidance, and Wavefront for path planning. [32]

## Following

Among semi-autonomous control modes shared control have been a popular operating mode. Following or using companion to follow is described as shared control in most of the researches. Intelligent wheelchair could track the companion's body position or the orientation by using laser range sensors or Lidars based on Kalman filter and data association estimate the guide's footprint [136–139].

A cubic spline generates a target path for the wheelchair using position data of the footprint of the companion. Also there was a research on a technology which allows the wheelchair to navigate without knowing the companion's destination. This was done using a destination estimating model to navigate with the companion[39].multi-wheelchair formation controls were introduced to make the communication easy with companions in order to enable a large group of disabled

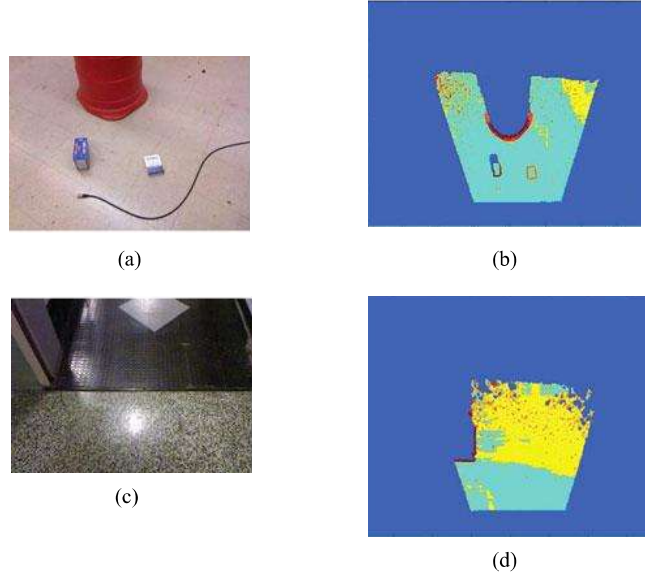


Figure 2.23: Determining navigability of terrain using point cloud data from a Microsoft Kinect. (a) RGB image floor type 1 (F1) with an obstacle and a few bumps. (b) Point cloud map of F1 indicating obstacles with red, flat safe terrain in light blue, and bumps in shades of orange and yellow. (c) RGB image floor type 2 (F2) with a doorpost and a terrain change from smooth to bumpy. (d) Point cloud map of F2. [140]

people at once[40].The wheelchair is controlled while maintaining the formation through plotting a path  $X$  defined by the model trajectory. Then a path for each wheelchair ( $X_1$ ;  $X_2$ ) is calculated by keeping a small distance from  $X$ .

## Localization and Mapping

A major challenge in developing intelligent wheelchairs is the development of a robust reliable localization and navigation system in both indoor and outdoor environments. Since the intelligent wheelchair needs to safely navigate on roads/sidewalks, it is required that the localization accuracy be within a range of a few centimeters. The main challenge for outdoor localization is that the GPS are not always reliable and robust, especially in tree-covered environments. The GPS measurements are integrated with attitude information from the onboard inertial measurement unit (IMU) to enhance the localization accuracy. Moreover, the developed navigation system also fuses the GPS/IMU measurements with the



wheel odometry information through an extended Kalman filter design [141,142]. Utilizing the odometry-enhanced fusion, the intelligent wheelchair will achieve high-accuracy localization even in GPS-denied environments [143,144]. Fig. 2.23 shows an example of obstacle detection using Microsoft’s Kinect [140]. An RGB image of a floor with an obstacle and a few bumps is shown side-by-side with a point cloud map of the same floor. Obstacles are red, flat safe terrain is light blue, and bumps are shades of orange and yellow. Three-dimensional point cloud data can also be displayed as a 2-D birds eye view of the intelligent wheelchair’s environment. Using spherical vision cameras like the BGR Ladybug 2 and applying methods like the improved Prewitt edge detection [145], intelligent wheelchairs can detect obstacles in most of the indoor environments.

## **Navigational Assistance**

An semi-autonomous obstacle avoidance was accomplished by Rofer et al. for a rear-wheel drive intelligent wheelchair, where the front active castor wheels are always rotated by motors to match the orientation of the current driving direction [146]. There was another implementation of this mode in multiple processes on a nimble rocket by Viswanathan et al. 2011 that targets visually impaired people [147]. That was consisted with a collision detector which detects collisions in the front and stopping the intelligent wheelchair approximately 1m from the obstacle. Also system included a Path planner which had a global map and estimated initial position. Visual odometry produced the optimal route towards specified location and deviations from the optimal route are determined by the trajectory. Final process was the Prompter which used a Partially Observable Markov Decision Process (POMDP). This estimated the user’s ability to navigate to the specified location through past experience.

Poorten et al. introduced a set of novel haptic guidance algorithms intended to provide intuitive and reliable assistance for wheelchair navigation through narrow or crowded spaces [148]. Tomari et al. propose a method of navigation in

crowded indoor environments based on the observation of people’s head information obtained from color and range images [149]. Initially, head regions in the color image are tracked and their orientations are estimated; then, the head orientation data are integrated with the head position data in the range image to determine the wheelchair motion so that it can smoothly move among humans.

## **2.3 Human Factors in the Intelligent Wheelchair**

User comfort is the most important aspect of an intelligent wheelchair as it indicates how successful it is in meeting the user requirements. Hence, human factors that improve and disrupt the relationship between the user and the wheelchair have to be considered when developing an intelligent wheelchair. This section outlines the human factors that have been mentioned in the literature and how they have been implemented on the intelligent wheelchairs.

### **2.3.1 Human–Robot Interaction**

A recent analysis of the available literature on trust and human–robot interaction (HRI) found that robot performance and attributes were the largest contributors to the development of trust in HRI. Environmental factors played only a moderate role [150].

In a discussion on the unique technical, ethical, and legal challenges facing HRI practitioners when designing robots for human social environments, Riek and Howard argue that the affordance of all rights and protections ordinarily assumed in human–human interactions apply to HRI and propose a code of ethics for the profession [151]. For an example assistive robots like intelligent wheelchair needs to safeguard the privacy and work alongside other ethical boundaries.

### 2.3.2 Learning

A program of research that include a mixed-methods approach, using lab-based, qualitative and quantitative methodologies spreading through five key research projects have introduced by a team of 18 clinical researchers at the University of British Columbia. They intended to test their collaboratively-controlled wheelchair with the Wheelchair Skills Program [32]. Another group of researchers at University of Naples (Gironimo et al. 2013) used virtual reality to get user evaluation on effectiveness and satisfaction including the quantitative measures [152]. It is very important to conduct user studies among the actual users of wheelchairs, elderly and disabled. Even if you make the safest and most effective intelligent wheelchair it will have no use if it doesn't have the user acceptance. Experimental results with elderly participants at a pseudo resident home reveals that the elderly prefer appropriate utterances from wheelchairs to reduce their anxieties and also they prefer more compromising wheeling speed as speed preference change with different person.

### 2.3.3 Physiology

Intelligent wheelchair users are involved in some accidents once in a while. Most common are falls off of the wheelchair due to inclined surfaces, so researchers at the Kyoto Institute of Technology measure the physiological indices when the wheelchair is inclined, in order to evaluate the physical strains on the human body [153]. Their results show that even though the contact area does not get higher as the incline angle gets higher, the distribution of high pressure area gets lower as the angle gets higher; therefore, people feel uncomfortable as the inclination gets higher. Older adults typically receive little or no mobility training when they receive a wheelchair and are, therefore, more likely to experience an accident. In order to accommodate this underserved population, Giesbrecht et al. developed a therapist monitored wheelchair skills home training program deliv-

ered via a computer tablet [154]. To optimize efficacy and adherence, principles of self-efficacy and adult learning theory were foundational in the program design. A study with 23 participants by M. Jipp of the German Aerospace Center in 2012 found that participants with lower fine motor abilities had more collisions and required more time for reaching goals. Adapting the wheelchair's level of automation to these fine motor abilities can improve indoor safety and efficiency [155].

#### **2.3.4 Social Issues**

Social issues speaks to the fact that human beings in every way a social being. Every human being ,be it disabled or not, elderly or young will have dignity and other social images and ideologies. So assistive robotics and Intelligent Wheelchair approaches should consider the social being in whole. Core aspects of user perspectives on assistive devices including Intelligent Wheelchair are identified through a study of data in the form of 55 letters from 33 Danish citizens in 2014. Those are quality of life, realization of personal goals, keeping up roles, positive self-image, personal dignity, independence, activities and participation, self-care and security, lack of access in surroundings, professional domination of assistive device area, cultural stigma of negative symbolic value, and cumbersome standardized devices [156].

This study defined several factors that will persuade a person with mobility impairment to withdraw from public activities.

- Individual: when body function is compromise. pain, strength, and endurance associated with body structure
- Physical environment: inaccessible locations and difficult and rude navigation.
- Social environment: social attitudes and level of available care.
- Technology devices: wheelchairs available of low-quality, inappropriate and

unfit.

- Contextual factors: Age and personal ability and self-confidence with wheelchair use.

## 2.4 Object Manipulation

Wheelchair users prefer a assistance of a robotic arm for performing ADL. Several researches can be found in the literature where robotic arms are mounted on wheelchairs as an user assistance. In 1998, Bath Institute of Medical Engineering, UK developed a wheelchair with a manipulator. Afterwards many researches have been carried out in this regard in order to enable the pick and place tasks for the wheelchair user. However, the dexterity of the tasks is enabled through the dexterity of the manipulator. With the development of the dexterous table top manipulators like Kinova's MICO and JACO manipulators, the tendency to incorporate robotic arms to wheelchairs have been increased compared to the wheelchair researches carried before 2014.

Even though researches have achieved success in pick and place tasks through wheelchair mounted robotic manipulators, intelligent object manipulation is still to be addressed through the researches. Intelligent object manipulation has several aspects which should to be considered for effective object manipulation. Various objects possess attributes which are unique to them. When manipulating the objects, these attributes should be taken in to the account. Moreover, placing the objects should be done according to the user preference. In order to achieve that a user study should be performed. Since there is no such evidence in the literature, the research topic of object manipulation on a wheelchair has a wide range of area to be addressed through future researches.

There are few systems which have implemented object handling and placement on a table top. Approach proposed in [163] to place multiple objects can stack

objects considering the stability and placing constrictions. However it does not include the relationship with the user's living preferences such as preferred hand



(a)



(b)



(c)



(d)



(e)



(f)

Figure 2.24: Wheelchairs with robotic manipulators (a) The Weston Wheelchair [157] (b) The Raptor Arm [158] (c) The Manus Arm [159] (d) The Mats [160] (e) DORA (f) PerMMA [161] (g) JACO [162]

or object attribute interrelationships. System implemented in [164] is focusing on rearranging objects on a cluttered surface. However it fails to consider human attributes regarding object placement or the spatial constrictions on the surface.

Schiffer et al. in [165] introduced a method for reasoning the spatial relationships between objects on a tabletop considering the uncertain positioning information. However, this system doesn't consider relationships between objects and their attributes. A method [166] was suggested in order to manipulate objects on a table considering vocal instructions. In here uncertain information regarding the placement was considered and object attributes were not considered. The system in [166] is used to ground the spatial relations about objects on top of table using natural language instructions. However these are not with respect to preferred hand or activity or object relationships. Further system mentioned in [167] has considered spatial categories and uncertain information in placing an object on a tabletop. However it has used only one type of object and hence it doesn't consider object interrelationships. All these systems are implemented by a person external to a table top and haven't considered someone using a wheelchair tray or table to function. [168] Therefore whole object placement context changes and both spatial requirements and human interactions will be different.

A summary of the findings revealed through the literature review is depicted in Fig. 2.25. The figure also summarizes the research gap discovered through the literature review. The aspects that are addressed through this thesis is highlighted in the column 3.

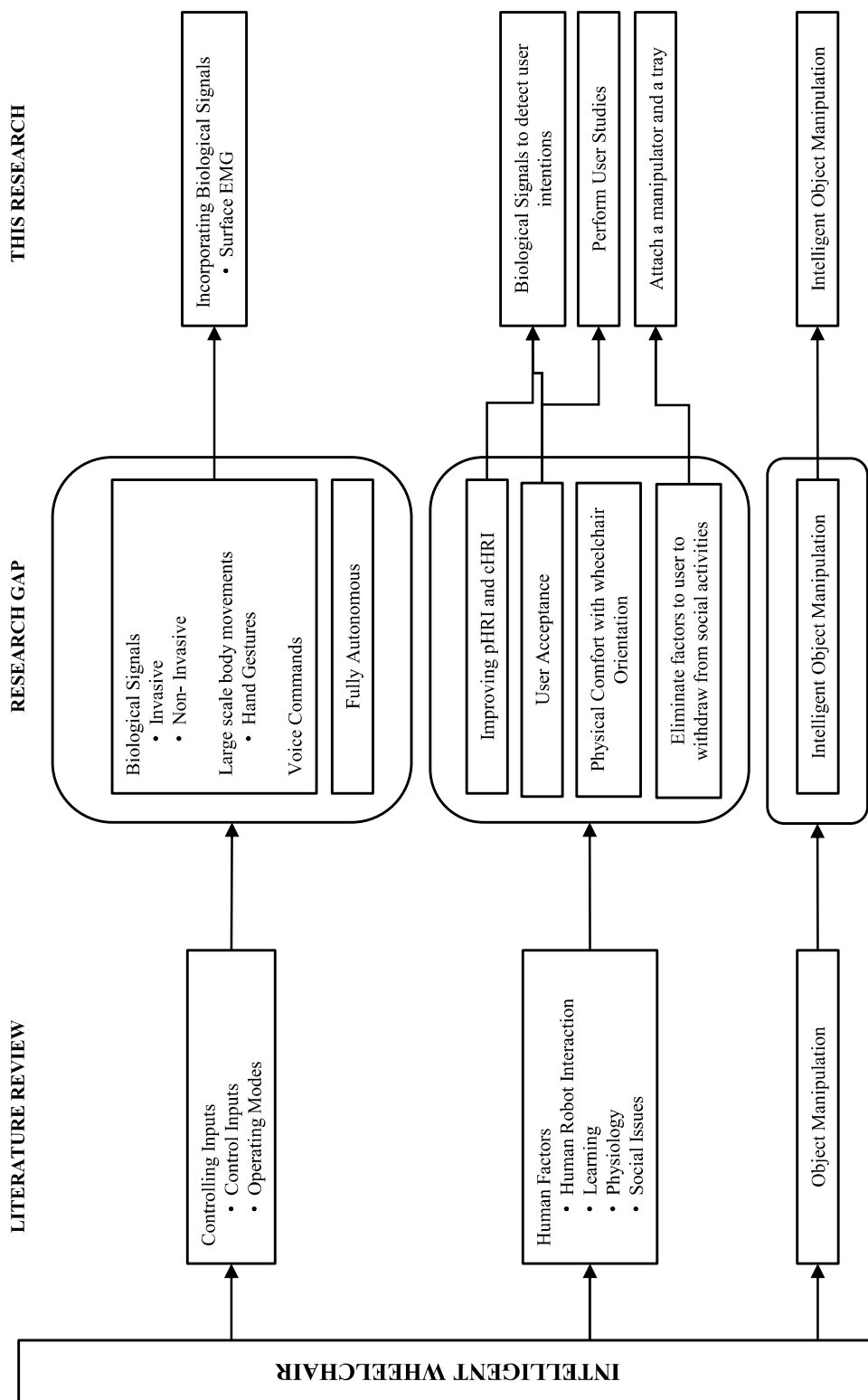


Figure 2.25: Summary of the literature review and the aspects addressed by this thesis



## INTELLIGENT WHEELCHAIR CONTROLLER

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This chapter describes the steps involved in developing the intelligent wheelchair controller. As the proposed controller is developed for a commercially available electric wheelchair (Jazzy Air, Pride Mobility Products) by passing the existing joystick based input feeding to the wheelchair was done as the first step. Next EMG based controller for navigation and detecting the intention for the use of the wheelchair manipulator was developed. With the participation of both male and female healthy subjects developed EMG based controller was tested for its adaptability with the different subjects. Finally this chapter describes the human study performed to gather required data for intelligent object manipulation for the wheelchair user for two scenarios: situation based object arrangement and the object arrangement based on the attributes of the objects. With few modifications controller for the whole system including the intelligent object manipulation is implemented in the simulation environment and the complete description of it is described in Chapter 4.

### 3.1 Interfacing PC and Existing Electric Wheelchair

As the first step of developing the wheelchair controller, existing electric wheelchair (Jazzy Air, Pride Mobility) and the PC was interfaced to give the navigational control input commands to the wheelchair through the PC. Wheelchair user can send the navigational command to the micro-controller through serial communica-

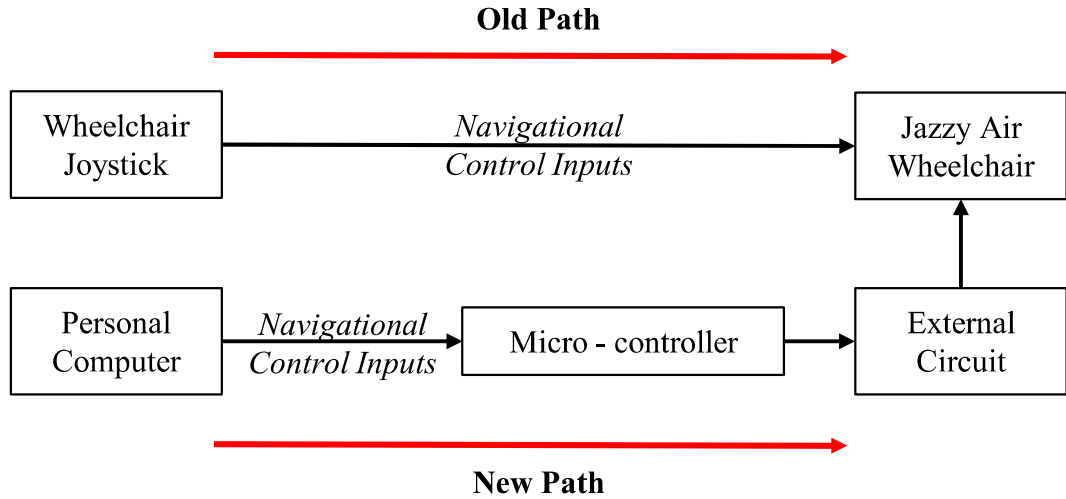


Figure 3.1: Navigational command control input path

tion. Micro-controller then generates the required Pulse Width Modulus (PWM) for the external circuit. Together with the external circuit new path can mimic the joystick functions (see Fig. 3.1).

A,W,S,D key inputs to the PC generate the navigation commands Left, For-



Figure 3.2: Navigating wheelchair through a PC Inputs

ward, Backward and Right respectively just like in the most of the PC games. Key press of button “M” is designed to replicate the neutral position of the joystick. Later, this concept is adapted for the for the simulation described in Chapter 4. Fig. 3.2 shows an external collaborator of this research navigating the wheelchair while providing the navigational inputs to the wheelchair using a PC (Laptop).

This method uses the wheelchair’s default velocity setting to navigate. Moreover, while using this interface, seat height adjusting capability of the wheelchair through the joystick is disabled.

### **3.2 EMG based Controller**

Even with the advancements of the intelligent wheelchair researches, wheelchair users who have trans-radial/ trans-humeral amputation and have partial limb functions are still affected by the fact that the existing IWs cannot help them to improve their situation. In order to perform ADL wheelchair users have to ambulate from one place to another [169]. However, using the inherent joysticks of the powered wheelchairs cannot be used by the users with complications in the upper limb, for the fullest. Even though there are other modalities for controlling the wheelchairs such as sip and puff, hand gesture, touch pads, virtual joysticks, chin control, eye-blink, etc. they are less preferred among these wheelchair users as they have proven to be ineffective with these wheelchair users’ limitations with their physical conditions and due to the lack of the user friendliness of some modalities [170]. Moreover, voice command based controllers have achieved some success but they are ineffective as it would become inoperable with the environmental interferences in a noisy environment [171].

It is required to assess the factors that can lead wheelchair users with upper limb complications, to get on the IWs without getting frustrated with the func-

tionalities of them. Improving cognitive Human Robot Interaction (cHRI) can be an effective way of remedying the above mentioned issue [172, 173]. Incorporation of the electrophysiological signals such as Electromyography (EMG) [174], Electroencephalography (EEG) [175], Electrocorticography (ECoG) [176], etc., as a modality for IWs is a research area with an increasing demand in order to improve the cHRI between the wheelchair users and the IWs. Before becoming wheelchair users, wheelchair users could have gone through several surgeries which leave traumatic experience in their lives. Generally, wheelchair users do not prefer to under go further surgeries than they had to. Hence, invasive (surgical) methods to extract electrophysiological signals, such as intra-muscular EMG and ECoG are not preferred by the wheelchair users [176, 177]. Thus, the researches have been paying more interest towards the non-invasive methods such as surface EMG (sEMG) and EEG, than the invasive methods, in order to extract the electrophysiological signals for the IWs. Due to the low Signal to Noise Ratio (SNR) EEG signals are less preferred among the researches compared to the EMG signals which has higher SNR than of EEG [178].

Available EMG based controllers for IWs for wheelchair users with trans-humeral/ trans- radial amputees are always incorporated with another modality like voice, hand gestures [179], joysticks [180], etc. However, it is completely different scenario whenever the user has a healthy upper limb as there are lots of muscles for sEMG extraction to build standalone EMG based classifiers [181] and users can use their healthy upper limbs for object manipulation as well. In such cases, a simple joystick controller could achieve the desired tasks for the user. Unlike them, users with trans-humeral/ trans- radial amputation or with partial upper limb functions require a robotic manipulator to manipulate the objects for the user in addition to the fact that there are limited number of muscles available for signal extraction. Nowadays, it is common to have robot manipulator incorporated with the wheelchair in order to manipulate objects for the wheelchair user [175]. In most instances, the manipulator used only if the user requests for its assistance. Most common modalities that are being used for the detection for

this aspect are the hand gestures and the voice commands. As described above, these modalities have to be given up due to the factors like complications in the upper limbs and environmental disturbances.

This thesis proposes a versatile EMG based controlling method which can be used by users with trans- radial/ trans- humeral amputation and with partial upper limb functions for the navigation and for the detection of the intention of the user's inability to reach to grasp. The system is designed for a powered wheelchair which with a robot manipulator for the object handling tasks. The proposed controller uses 4 stages including the resting between the main two tasks: navigation input generation and the detection of intention to reach to grasp an object. An EMG based task switcher is used to switch between the tasks eliminating the requirement of another modality for the controller. The sequentially activated tasks are achieved through sEMG of 2 muscles of the neck, 2 biceps brachii of the two upper limb and the triceps brachii of the dominant arm.

### **3.2.1 Overview of the proposed EMG based Controller**

The proposed EMG based controlling system is designed for wheelchair users with trans- humeral/ trans- radial amputation and for the users with partial upper limb functions. Even though the system is designed mainly for the above mentioned categories of wheelchair users, it can be used by any type of wheelchair user who has the capability to move their arms fully or partially and has the ability to perform left and right rotations of the head.

Fig. 3.3 depicts the overview of the proposed EMG based system for the wheelchair. Raw EMG signals extracted from sternocleidomastoid muscles which are located in the neck area, biceps brachii of both upper limbs and the triceps brachii of the dominant arm are amplified through the EMG amplifier (16 channel Bagnoli<sup>TM</sup> desktop EMG system, DELSYS) and then fed in to the personal com-

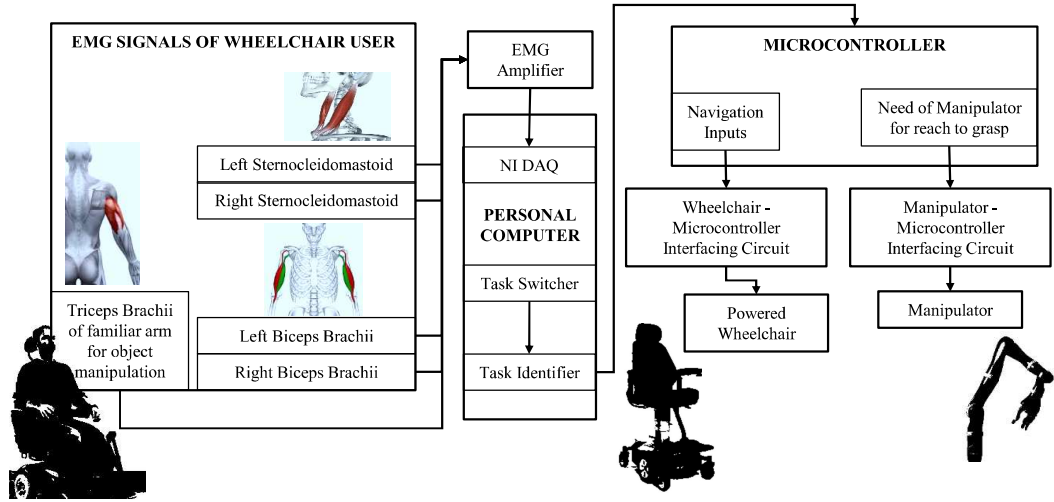


Figure 3.3: Overview of the EMG based Controller

puter via the Data Acquisition (DAQ) card (PCI - 6220, National Instruments). Raw EMG signals are then filtered through a band pass filter of 20Hz to 450Hz. The proposed system is designed to achieve two tasks on the wheelchair. First task is to generate navigational inputs for the wheelchair and the second task is to detect the user's intention to reach to grasp and object. Task Switcher (TS) is implemented to switch between the two tasks. Since there are two tasks achieved through the EMG based system a Task Identifier (TI) is implemented. Its main task is to identify the state which the wheelchair user is in at a given time. Task identifier passes the relevant information to the Microcontroller (ATmega, Atmel) to generate the required PWM inputs for the wheelchair and the PWM inputs for the robot manipulator. Here, the system is designed for a powered wheelchair (Jazzy Air, Pride Mobility Products® Corporation). Throughout the whole process, Root Mean Square (RMS) of the EMG signals have been used. Moreover, EMG based controlling system is developed as a Human in The Loop (HITL) system where the user gets the vision feedback from his/her eyes to control the system.

### 3.2.2 EMG for Navigation

RMS of the EMG signals of left and right sternocleidomastoid muscles and the biceps muscles of both hands are used for the Navigation purposes of the proposed system. Sternocleidomastoid muscles are activated during the left and right rotation of the head. It is common for humans to express their directional information using their head. This feature of the humans is adapted for this system too. In order to give the left and right commands to the wheelchair, user has to perform left and right head rotations and left and right sternocleidomastoid muscles will be activated respectively to perform the task. Since, this is a HITL system user can use his/her direct vision and the peripheral vision to control the the rotation of the wheelchair. It is possible to use the forward flexion/extension (F/E) of the head for the forward and backward motions of the wheelchair. Unlike in the head rotation motion, using forward F/E motion of head of the user has adverse effects towards navigation as the user cannot use neither of his/ her direct vision nor the peripheral vision for the acquiring of the vision feedback for the system (see Fig. 3.4). This occurs due to the fact that both vision feedbacks

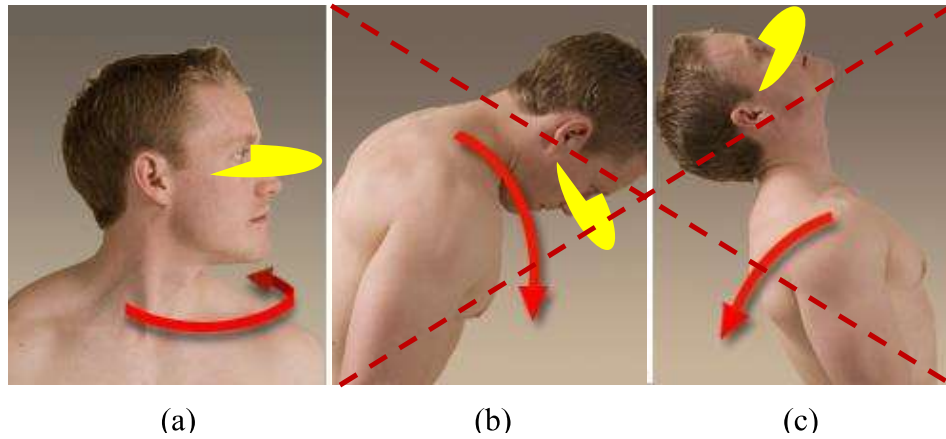


Figure 3.4: Human Vision changes during head motions. (a) Rotation of head (b) Forward Flexion of Head (c) Forward Extension of head. Head rotation can be used for the navigation input generation as the assistance of the vision is in the direction of the navigation. However, the assistance of peripheral vision or direct vision is not available in the direction of head motion if the forward flexion and extension of the head is used for the navigation input generation

are not aligning with the direction of the navigation (forward/ backward) of the wheelchair. Hence, the RMS of the EMG signals of the both biceps muscles are used for achieving the inputs for navigation in forward/backward directions. For the input of forward motion, user has to think (intend) to flex the right upper limb from elbow so that the right bicep would be activated. Same process has to be carried out through the left upper limb in order to achieve the inputs for the backward motion [182].

### **3.2.3 EMG for intention identification for reach to grasp**

Due to the partial functionality of wheelchair users' upper limbs, they cannot reach the objects successfully. More often, the objects are located out of their reach since their reachable workspace is reduced due to the complications of the arm. In the other cases (as discussed at the beginning of Section II), users only have a stump arm so that they cannot reach the objects at all. Here, the intention identification algorithm is designed mimicking the real life scenarios in reaching to grasp far objects. Healthy humans use their dominant arm to reach an object and if it is within their reach they grasp that object with that arm. However, if the objects are out of their reach but not far from their full extension of their arm, they try to push their arm little more. This phenomena is brought into the system where the wheelchair user has to try to push their arm or the stump arm from their maximum reach to further. This creates the EMG input required for the identification of the user's intention for reach to grasp [182].

### **3.2.4 Task Switcher (TS)**

As mentioned in the previous section, main task of TS is to switch the tasks from one to another. For that purpose TS is getting the EMG inputs from both Biceps brachii of both upper limbs. In the proposed system biceps are activated during forward/ backward navigation. However, there is no scenario where both



biceps are activated at once. In order to achieve this, wheelchair user has to think (intend) to flex both of his/her upper limbs from the elbows. Then, TS will receive the input to switch the task from the current task to next.

### 3.2.5 Task Identifier (TI)

There are mainly two tasks achieved through the proposed EMG based algorithm: generating navigation inputs for wheelchair and identifying the intention to reach to grasp. However, there is another intermediate task which has to be achieved through the proposed algorithm: resting state between the tasks. Here, resting implies that there is no task being carried out by the wheelchair at that moment. By default, wheelchair is set to be at rest. Hence it is taken as the State 1. After a TS, State 1 will be shifted to State 2: Navigation state. State 3 is again a resting state which will be achieved after a TS. After another TS, state will be shifted to State 4: Identification of intention to reach grasp. After State 4 is done user has to perform another TS which will shift TI to State 1.

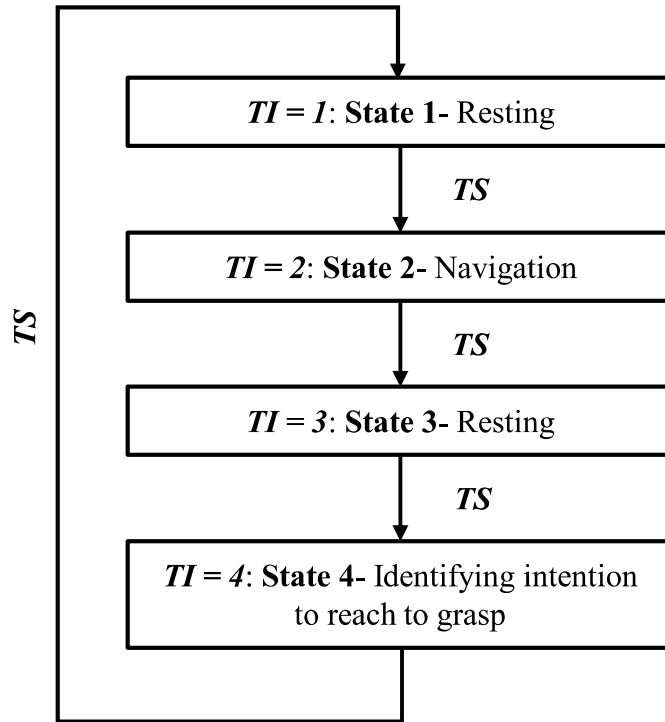


Figure 3.5: Task Shifting Sequence

Summary of the States shifting is depicted in Fig. 3.5. All the tasks are achieved sequentially in the order they are defined.

### 3.2.6 EMG based controlling Algorithm

RMS of the EMG signals for a sample size of 100 is calculated as of equation 3.1.

$$R_r = \sqrt{\frac{\sum_{i=t}^{t+N} S_i^2}{N}} \quad (3.1)$$

Here  $R_r$  ( $r = 1,2,3,4,5$ ) denotes the RMS value of the  $r^{th}$  channel.  $S_i$ ,  $N$  and  $t$  are the Raw EMG of  $r^{th}$  channel at a given time, sample size and the beginning of the sample respectively.  $R_1$ ,  $R_2$ ,  $R_3$ ,  $R_4$  and  $R_5$  stand for the RMS values of right bicep brachii, left bicep brachii, left sternocleidomastoid, right sternocleidomastoid and triceps brachii of the dominant hand respectively.

EMG based controlling algorithm is depicted in Algorithm 1. Here,  $D_1$ ,  $D_2$ ,  $D_3$  and  $D_4$  stand for the directional commands for navigation: forward, backward, left and right respectively.  $D_{Null}$  denotes the absence of the directional command and it implies the wheelchair to stop.  $D_{Nav}$  is the output sent to the microcontroller containing the directional command for the navigation.  $I_{inten}$  stands for the output that is sent to microcontroller to indicate the need of the manipulator for the reach to grasp task.  $R_{i,threshold}$  ( $i= 1,2,3,4,5$ ) values are defined according the user. In order to work with proposed EMG based controller a calibration has to be done before using it. During the calibration phase  $R_{i,threshold}$  values are defined by considering the Maximum Voluntary Contraction (MVC) of the muscle.

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**Algorithm 1:** EMG based controlling algorithm

---

**Input:**  $R_1, R_2, R_3, R_4, R_5$   
**Output:**  $D_{Nav}, I_{inten}$   
initialization;  
**while** *EMG available* **do**  
    **if**  $R_1 > R_{1,threshold} \ \&\ R_2 > R_{2,threshold}$  **then**  
         $TS \leftarrow True$   
    **else**  
         $TS \leftarrow False$   
    **end**  
    **if**  $TS == True$  **then**  
        **if**  $TI < 4$  **then**  
             $TI \leftarrow TI + 1$   
        **else**  
             $TI \leftarrow 1$   
        **end**  
    **else**  
        **if**  $TI == 2$  **then**  
            **if**  $R_r > R_{r,threshold}(r = 1, 2, 3, 4)$  **then**  
                 $D_{Nav} \leftarrow D_r$   
            **else**  
                 $D_{Nav} \leftarrow D_{Null}$   
            **end**  
        **else if**  $TI == 4$  **then**  
            **if**  $R_5 > R_{5,threshold}$  **then**  
                 $I_{inten} \leftarrow True$   
            **else**  
                 $I_{inten} \leftarrow False$   
            **end**  
        **else**  
             $D_{Nav} \leftarrow D_{Null}$   
             $I_{inten} \leftarrow False$   
        **end**  
    **end**  
**end**

---

### 3.2.7 Experiments

Experiments were carried out to monitor the performance of the proposed EMG based controller. Since, EMG tends to differ from person to person, adaptability of the implemented controller was tested with different human subjects. 4 healthy human subjects were participated for the experiment. 3 of them were

healthy male subjects whilst the other participant was a healthy female. For each of the participants, proposed controller was calibrated according to their EMG signal strength. During the calibration phase, only the  $R_{i,threshold}$  values per individual participant were changed. They were asked to perform the sequence of the tasks of the implemented controller (as in Fig.3.5) for 3 times by doing “simultaneous flexion of right and left elbows (For TS) → right elbow flexion (for forward navigation) → left elbow flexion (for backward navigation) → right rotation of head (for turning right) → left rotation of head (for turning left) → two simultaneous flexion of right and left elbows (for skipping the stage 3 - resting) → intend to reach a far object using their dominant arms (for detection of user’s intention to use the manipulator) → simultaneous flexion of right and left elbows (ends the sequence)” [Refer to Fig. 3.7]. A set of 3 trials is called as a Round. Between each trial in a round, a resting period of 2 minutes was imposed and 15 minutes of resting period was imposed between two rounds to avoid occurrence of the muscle fatigue of participants. Round 1 and 2 were done to calibrate the controller whilst Round 3 was carried out to validate the calibration.

### 3.2.8 Experimental Setup

Fig 3.6 shows the EMG electrode placements on the wheelchair users. Experimental setup is almost same as of Fig. 3.3. The main differences are that there is an external operator to calibrate the  $R_{i,threshold}$  values and the setup is concluded from the interfacing circuit of the joystick and the manipulator. The interfacing circuits contains an array of indicators to indicate the outputs. Each and every input has a corresponding indicator to indicate the generated output.

### 3.2.9 Results

Fig. 3.7 shows the steps involved in monitoring the efficacy of the implemented controller with a healthy subject. EMG signal variation during each activity is

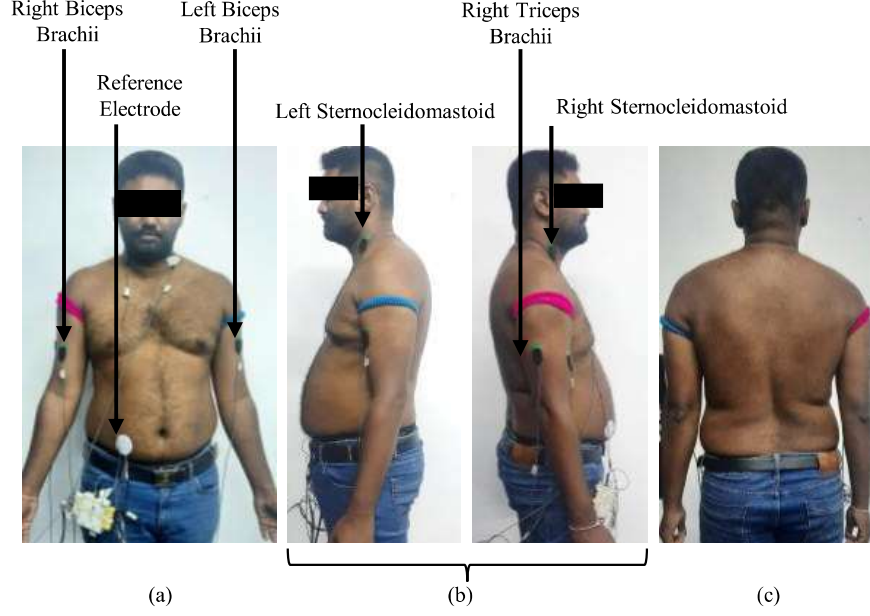


Figure 3.6: EMG Electrodes placement: (a) Anterior View (b) Lateral View (c) Posterior View

also depicted in Fig. 3.7. The spikes in the EMG plot depict the activation of the relevant muscles. Even though it can be seen that there is a spike in the biceps brachii of the dominant hand during the forward input generation in navigation and during TS, it was neglected as the RMS of it is below the  $R_{5,threshold}$  value. A detailed video taken after the trial 3 of Round 3 of the participant “P1” can be found in [182]. Here, the “Center” command stands for the  $D_{Null}$  in the Algorithm 1. Moreover, “Manipulator is Needed” output stands for the “**True**” state of  $I_{inten}$  in the Algorithm 1 whereas “Manipulator is not Needed” output stands for the the “**False**” state of  $I_{inten}$ . Indicators depict the navigation outputs :  $D_i$  ( $i=1,2,3,4$ ) and  $D_{Null}$  (center) during the State 2. Output for “**True**” state  $I_{inten}$  is also indicated by the indicator during the state 4. In order to show the real time outputs, a screen recording of the real time outputs is included in the video too. It also reveals that the implemented EMG based controller works smoothly with the user intentions. Moreover, during both State 2 and 4 controller is set set to be at  $D_{Null}$  and “**False**” state of  $I_{inten}$  respectively, in case of loose contact between the EMG electrode and the muscle surface. This aspect is implemented as a fail safe mechanism in order to avoid mishaps due to unintended movements

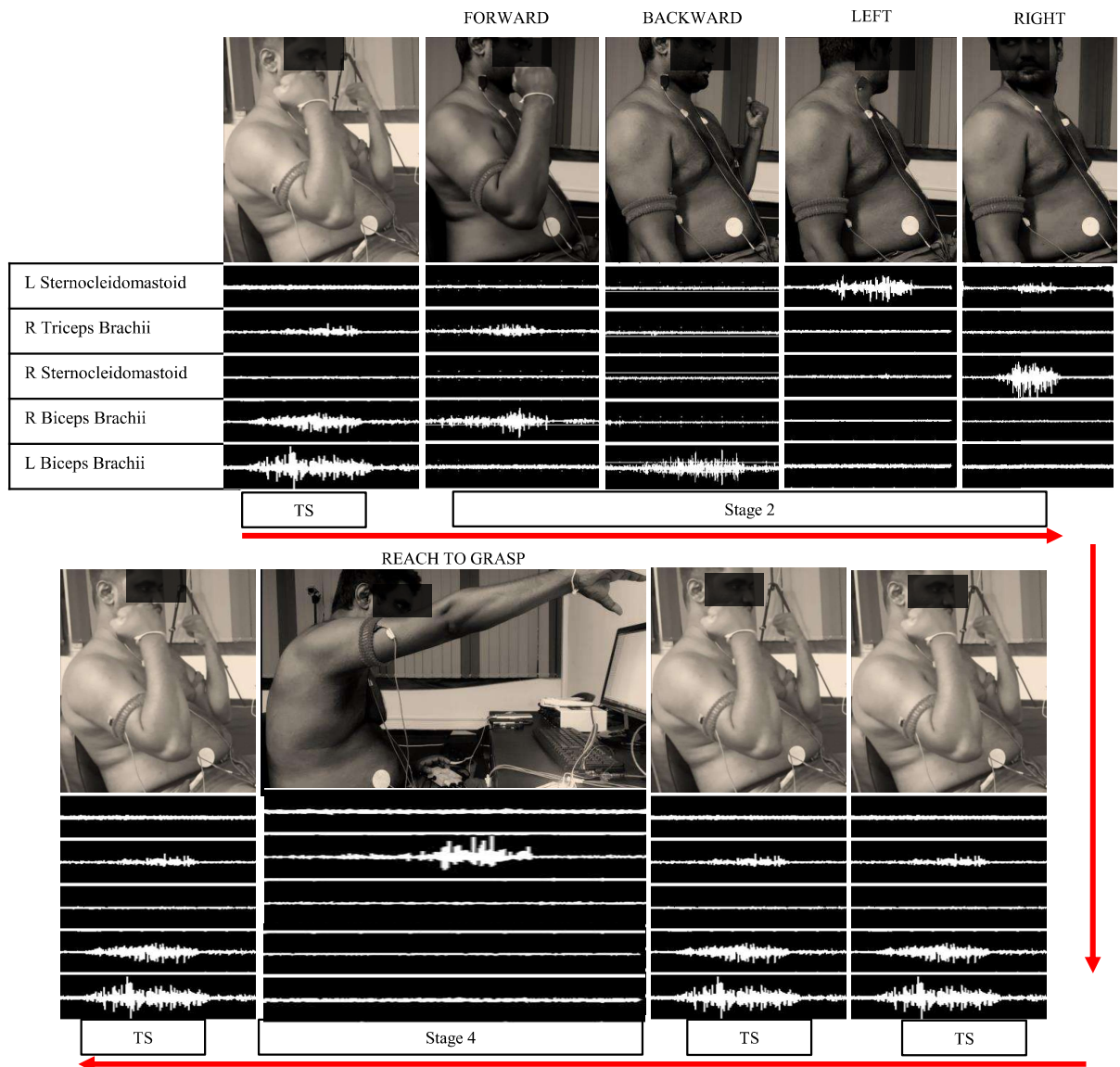


Figure 3.7: Experiment Procedure: Participants were asked to perform the tasks in the chronological order as of the figure. EMG variation of the 5 muscles during those motions are also depicted in the figure

of both wheelchair and the manipulator.

Table 3.1: Calibrated  $R_{i,threshold}$  values for the participants

| Participant Number | Age (years) | Gender | Threshold RMS Values for $R_{i,threshold}$ ( $i = 1, 2, 3, 4, 5$ ) |                   |                   |                   |                   | Round   |
|--------------------|-------------|--------|--------------------------------------------------------------------|-------------------|-------------------|-------------------|-------------------|---------|
|                    |             |        | $R_{1,threshold}$                                                  | $R_{2,threshold}$ | $R_{3,threshold}$ | $R_{4,threshold}$ | $R_{5,threshold}$ |         |
| P1                 | 31          | Male   | 0.20                                                               | 0.20              | 0.30              | 0.30              | 0.070             | Round 1 |
|                    |             |        | 0.20                                                               | 0.20              | 0.30              | 0.30              | 0.070             | Round 2 |
|                    |             |        | 0.20                                                               | 0.20              | 0.30              | 0.30              | 0.070             | Round 3 |
| P2                 | 29          | Male   | 0.20                                                               | 0.20              | 0.30              | 0.30              | 0.070             | Round 1 |
|                    |             |        | 0.30                                                               | 0.30              | 0.37              | 0.37              | 0.081             | Round 2 |
|                    |             |        | 0.28                                                               | 0.28              | 0.37              | 0.37              | 0.081             | Round 3 |
| P3                 | 27          | Female | 0.20                                                               | 0.20              | 0.30              | 0.30              | 0.070             | Round 1 |
|                    |             |        | 0.18                                                               | 0.18              | 0.25              | 0.25              | 0.060             | Round 2 |
|                    |             |        | 0.19                                                               | 0.19              | 0.27              | 0.27              | 0.060             | Round 3 |
| P4                 | 26          | Male   | 0.20                                                               | 0.20              | 0.30              | 0.30              | 0.070             | Round 1 |
|                    |             |        | 0.22                                                               | 0.22              | 0.32              | 0.32              | 0.076             | Round 2 |
|                    |             |        | 0.22                                                               | 0.22              | 0.32              | 0.32              | 0.076             | Round 3 |

Table 3.1 contains the  $R_{i,threshold}$  ( $i=1,2,3,4,5$ ) values for all four participants of the experiment. All the participants were healthy and had a mean age of 28 (standard deviation 1.87). Both male and female subjects were participated for this experiment to expand the versatility of the experiment.  $R_{i,threshold}$  values of the participant “P1” were set for the Round 1 of the other participants. From there, fine tuning was done during the next six trials of the two rounds. EMG signals extracted from the muscles are filtered through a band-pass filter of 20Hz to 450Hz and then they were amplified to 10k. After that the RMS of the extracted EMG signal is calculated. It can be seen that the values are changing from participant to participant. However, the mean difference in the values are about  $\pm 0.03$ , 0.03, 0.09, 0.09 and 0.007 for  $R_{i,threshold}$  ( $i=1,2,3,4$ ) respectively. These changes can be occurred due to various reasons. Participant’s healthiness, age, muscle fatigue, tiredness, fat percentage, etc. are among those reasons. However, these values can be drastically varied if the EMG signals are extracted from an amputee or from a patient with partial motor functions. In order to use this EMG based controller for such users, EMG signals may have to be amplified to a higher level than of this experiment. Most importantly, such persons will have to go through physio-therapeutical process before being able to use this controller. The other fact that revealed by this experiment is that this EMG based controller can be used for variety of users with ease. Even though the EMG signals are not same for every user, the controller can be adapted to match the user’s EMG signal strength.



### 3.3 Preliminary Human Study on Intelligent object handling

Increase of population with walking impairments has become one of the mostly discussed research topics of the modern era. Wheelchair assistance is the most preferred alternative for those who are suffering with these conditions [183]. Modern day wheelchairs contain sophisticated facilities to make life easy for wheelchair users. With the assistance of these wheelchairs, users have been able to perform service tasks of daily life effectively and with ease. Furthermore, these sophisticated wheelchairs have uplifted the living standards of the disabled [184].

There are several types of powered wheelchairs at present. Most of those can be classified according to the expected tasks from the wheelchair [185]. From an ordinary assistant for the user, to move from one place to another, wheelchair has developed to a state where it is used as an intelligent assistant for the disabled people. In order to enhance the assistance given to the user those wheelchairs possess several peripherals like robotic arms, trays, display units and etc.

Wheelchair users often prefer to keep the useful objects like cups, plates, books, mobile phones and etc close to them. For this purpose, wheelchairs come with collapsible trays attached to them or as external peripheral to the wheelchair [186]. For the further assistance robotic arms are attached to the wheelchair for the pick and place tasks. In order to robotic arm to place the objects on the wheelchair tray, it must contain pre - programmed spatial parameters of the wheelchair tray according to the user activities and object attributes. Moreover, attached robotic arm should consists of information required for spatial arrangement of the object on the wheelchair tray.

All the wheelchair users are mentally affected due to their physical disabilities. Enhancing the Cognitive Human (wheelchair user) Robot (wheelchair) Interaction (CHRI) can be used to ease their mental agony [172]. There are several variables which affect the user preference in object arrangement. If the robot

arm does not satisfy these variables, a conflict between the user preference and the deliverables of the robot arm will be generated. This conflict can lead the wheelchair user to give up using the robot arm for object handling and may incline to go for the support of external caregiver eventually. Hence, it is pertinent to understand and predict the user preferences in arranging the objects on the wheelchair tray if the object handling is done by means of a robotic arm.

It is impossible to design a model which can depict the wheelchair user preference for object arranging because these models would depend on the user emotions too. In order to minimize the discrepancies, information gathered from a human study can be used. For an effective system for object arrangement on a wheelchair tray, human studies should be conducted for different variables regarding this matter. Handedness of the wheelchair user can be identified as the most obvious variable for arranging objects on the wheelchair. If the objects are arranged in a manner which complies with the user's handedness, user can easily perform their tasks. This will result in enhancing CHRI.

Another variable that should be addressed to arrange the objects in a effective manner is arranging objects according to their respective attributes. Attributes are mostly dependent on the user's perspective. In both cases it is evident that there is a need for a study on the user preferences in handling object on the wheelchair tray. This paper describes a study carried out to determine the preferences of the wheelchair users in arranging objects on a wheelchair tray. Experiments have been designed to monitor the patterns which can be emerged in the above mentioned scenario.

### **3.3.1 Conducted Human Study**

Human study was carried out to monitor the user preferences and how they use their past experience/knowledge to arrange the objects on a wheelchair tray. Subjects were allowed to arrange the objects depending on their handedness and

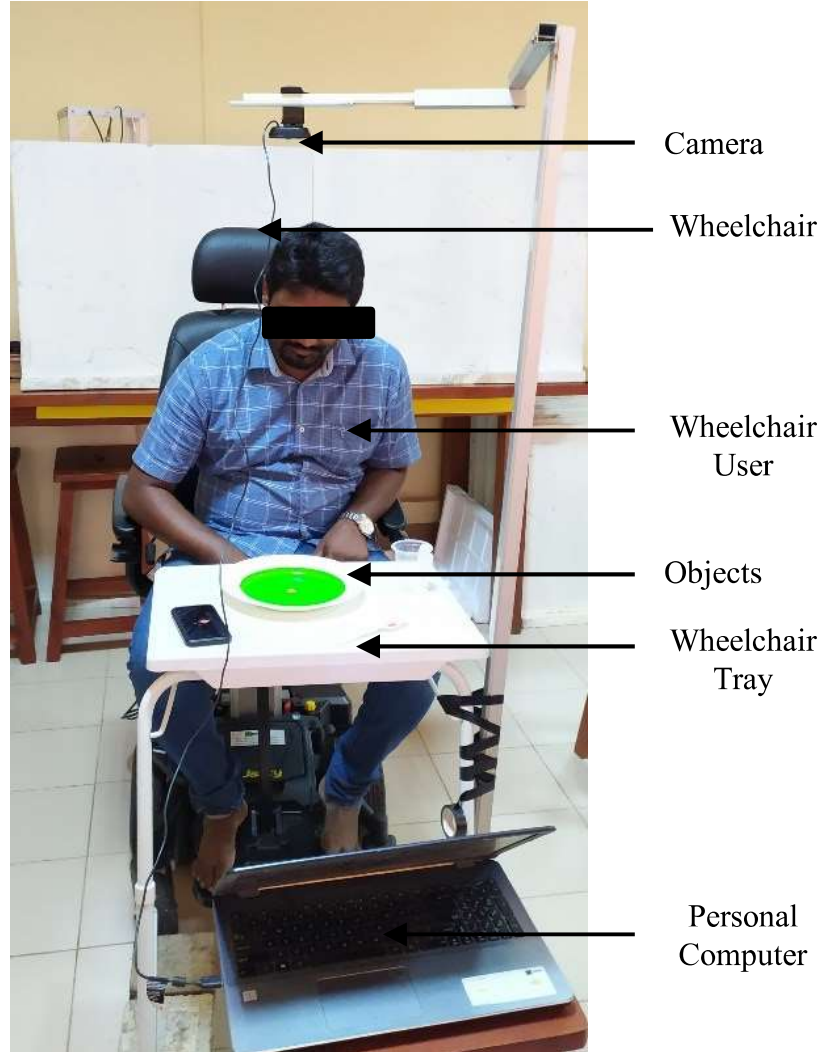


Figure 3.8: Experimental Setup

the attributes of the objects respectively. Obtained results were then analyzed to investigate for the patterns emerged through the trials. Experimental setup consists of a wheelchair, wheelchair tray (dimensions:  $53\text{cm} \times 36\text{cm}$ ), wheelchair user, camera, personal computer(PC) and objects which were planned to keep on the tray [see Fig. 3.8]. Using the camera, object arrangement on the wheelchair tray was captured and sent to the personal computer. In order to identify the positions of the objects markers were pasted on the objects [see Fig. 3.10]. MATLAB image processing toolbox was used to extract the information of the captured image from the camera. Location assignments on the objects captured image through MATLAB is depicted in Fig. 3.9. However, the coordinates depicted in

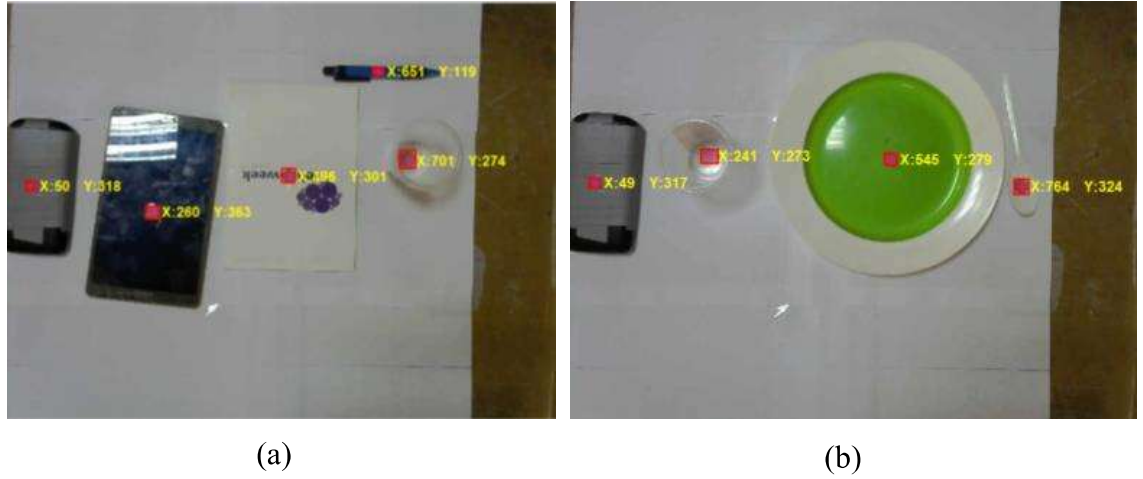


Figure 3.9: Location calculated through the captured images. (a). Working/ Studying Environment (b). Dining Environment

the figure are converted to match their exact locations on the tray.

### 3.3.2 Situation based Object arrangement

This study was carried out to determine whether there is an effect on the object arrangement on the wheelchair tray with the situation and the handedness of the users. 20 healthy subjects were participated for this study (age range 23 to 60 (Mean-26.35, SD-9.85)). Out of the 20 subjects 10 were right handed and the other 10 were left handed. Depending on the situation, subjects were given objects and were instructed to arrange them on the wheelchair tray as they preferred.

The list of objects consists of a pen, a book, a tablet (tab), a mobile phone, a cup, a spoon and a plate [see Fig 3.10 and 3.11]. Subjects were asked to imagine a studying/ working environment and were given the pen, book, tab, mobile phone and the cup to arrange them on the wheelchair tray in a manner which they would feel convenient for the mentioned environment. Each of them were asked to repeat the same activity for 10 times. Between Trials 5 minute break was imposed. Same protocol was carried out for dining environment with the cup, spoon, plate and mobile phone as the objects. Object arrangement was captured

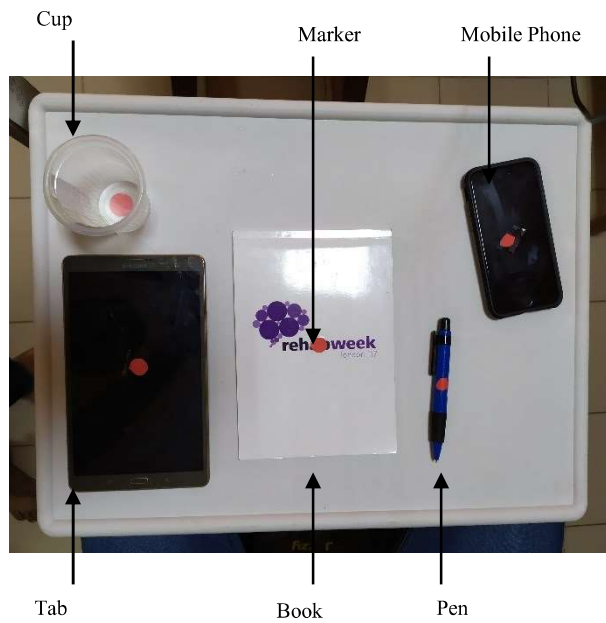


Figure 3.10: Objects for Studying/Working

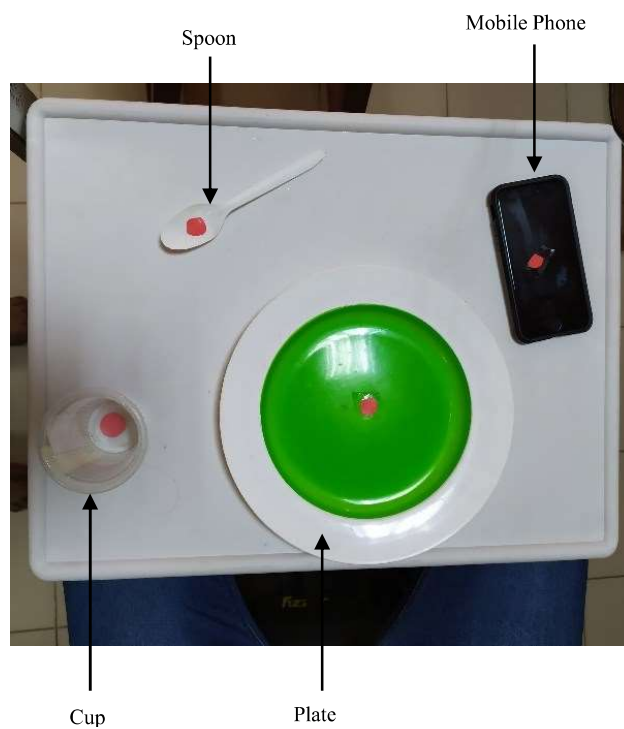


Figure 3.11: Objects for Dining

from the camera and sent to PC for further analysis of the acquired data.

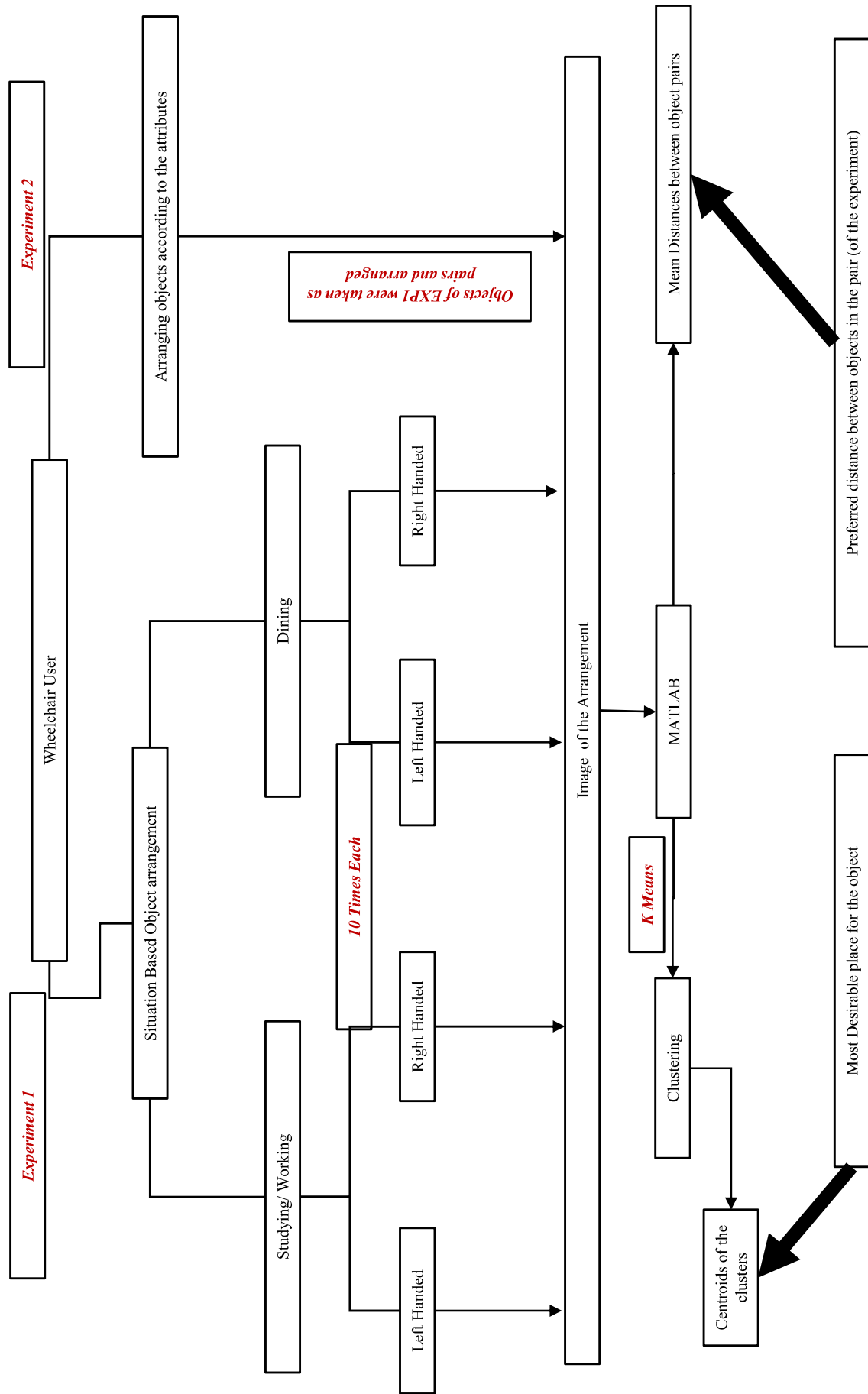


Figure 3.12: Experiment Protocol

### 3.3.3 Object arrangement based on the attributes of the objects

Second study was carried out to investigate how the wheelchair users arrange the objects on the wheelchair tray according the attributes of the respective objects. Each of the objects mentioned above has unique attributes which differs them from each other. For example mobile phone is an electronic device which is generally kept away from the liquid surfaces and situations where it can get contacted with liquids potentially. Hypothetically, wheelchair user might consider this aspect when keeping mobile phone and cup of water or he/she may not consider that fact at all. In order to obtain a vivid understanding about how the wheelchair users would arrange those unique objects, subjects were instructed to place the given objects as they prefer. 10 subjects were used for this study. Those objects were given as pairs in order to get a direct and clear response form the subject for the distance between the two objects. Those pairs were book-cup, book-phone, book-pen, book-tab, tab-phone, tab-cup, plate-cup, plate-phone, plate-spoon and phone-cup. Considering the unlikely occurrence of the need of some pairs like plate-pen, pen-spoon and etc., they were omitted from the study.

### 3.3.4 Results

Fig. 3.13. (a) and Fig. 3.13. (b) depict the data points recorded for object arrangements of the subjects for a studying/ working environment and dining environment respectively. K means clustering algorithm is used to identify the clusters of the recorded data and labelled the identified clusters after carefully preprocessing the data set taken for the preferences to filter out the outliers. Centroids of the identified clusters were calculated for the potential implementation of the findings for the intelligent object manipulation. Implementation of the findings is described in Chapter 4.

It can be identified that there are common patterns for both left handed and right handed users for studying/working environment from Fig. 3.14. (a). Both

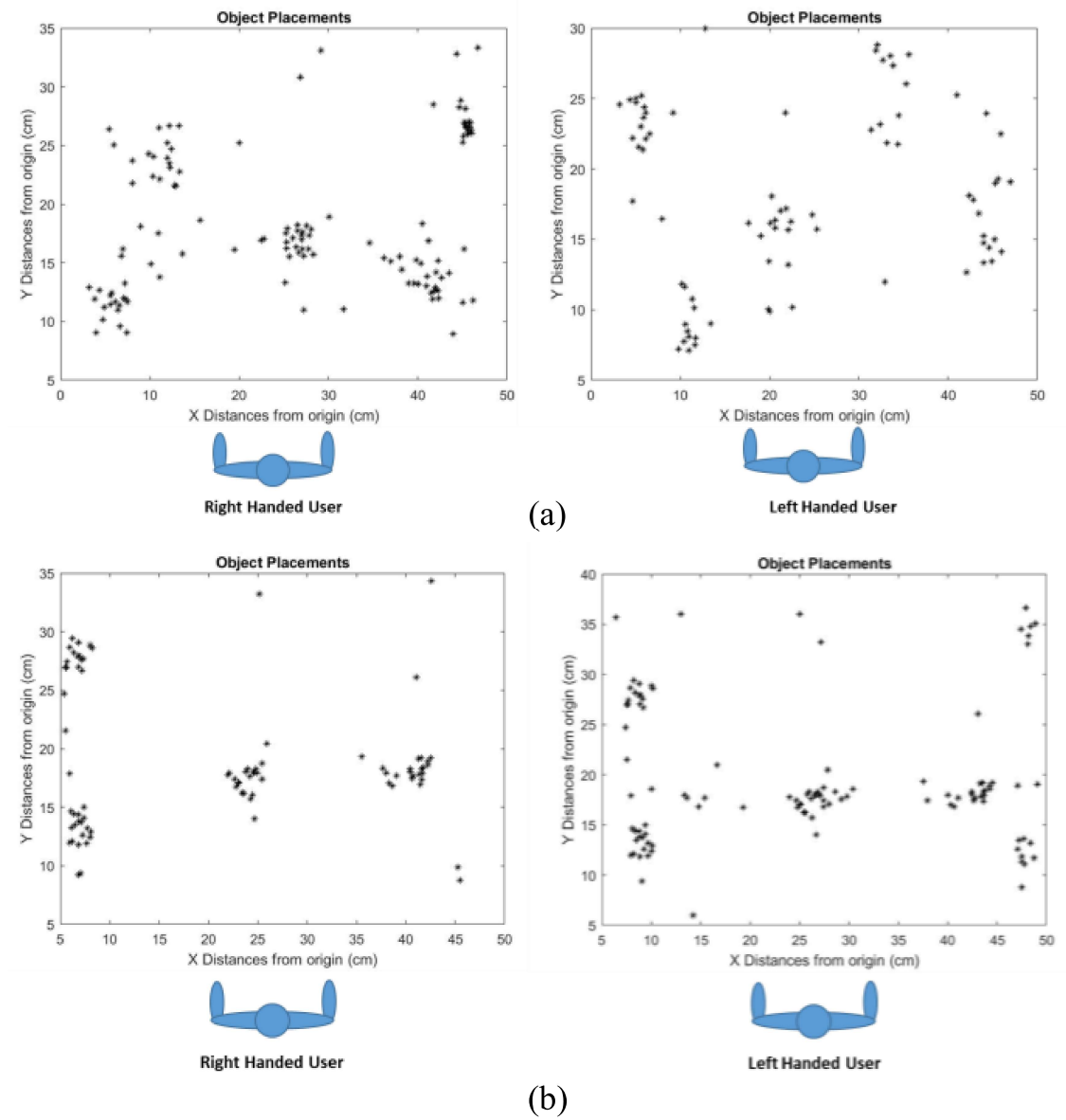


Figure 3.13: Responses of the subjects for object arrangement on the wheelchair tray for (a) Studying/ Working environment (b) Dining Environment

left handed and right handed users have kept the pen at the side of their familiar hand. Moreover, there is an obvious pattern in the results for the book. Both right and left handed users have a tendency to keep the book in the mid area. Furthermore, majority of the subjects has kept the cup at their left side. Even though the fact remains as such, right handed users have kept the cup closer to them whereas the left handed users have kept it towards the far left corner. It may have been occurred due to the fact that the left handed users are concerned



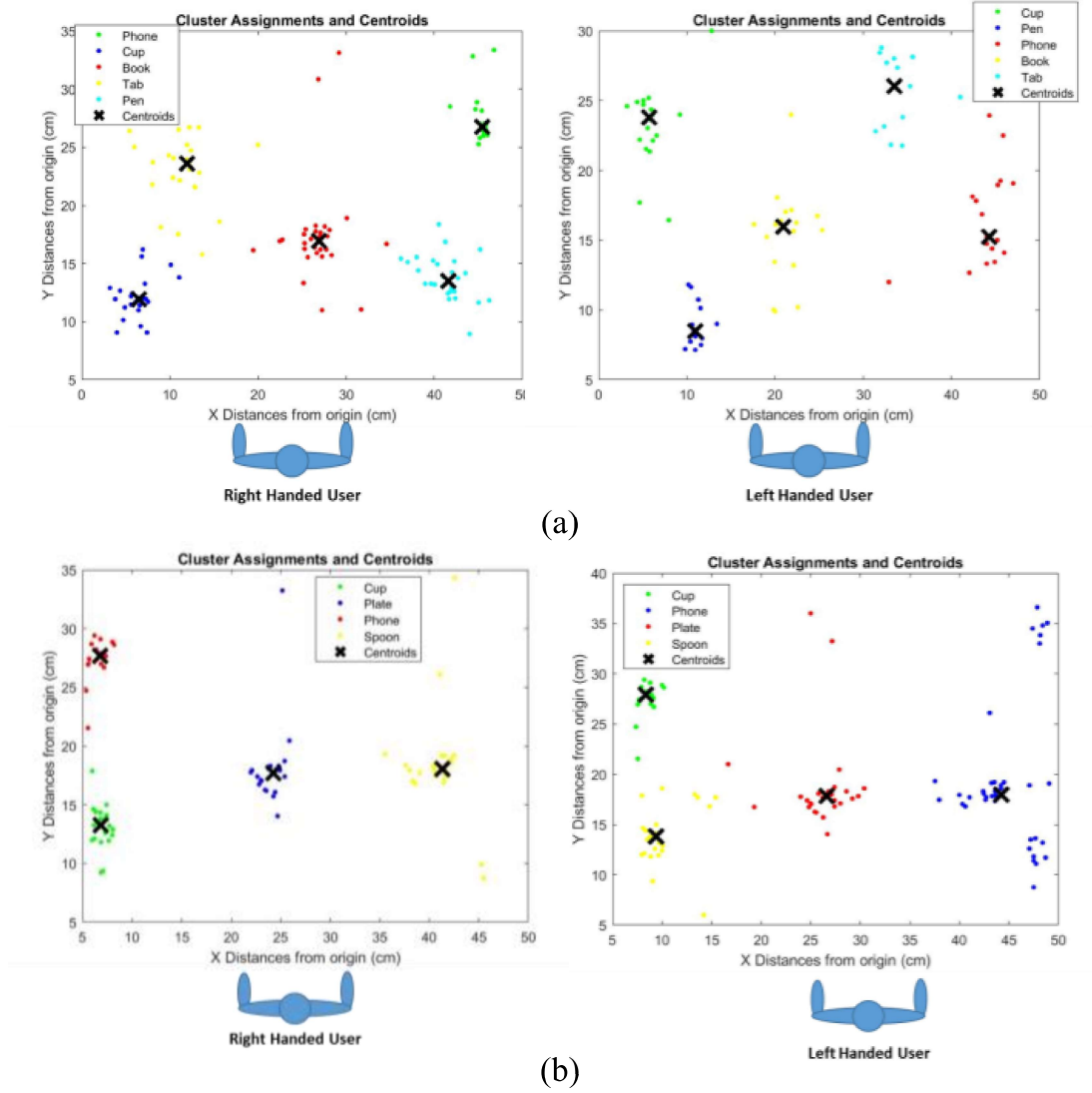


Figure 3.14: Clustered Responses of the subjects for object arrangement on the wheelchair tray for (a) Studying/ Working environment (b) Dining Environment. “X” denotes the centroid of the cluster

about the mishaps that could happen by hitting the cup with their writing during studying/ working. Since, right handed user is less affected by this scenario compared to the left handed user, right handed subjects have kept the cup closer to them than the left handed subjects. It is evident that placement of the mobile phone is not affected by the handedness of the user. Both types of users have kept the phone at a moderate distance form the bottom edge of the tray towards the right side of the tray. Placement distance of the tablet from the bottom edge

of the tray is almost the same for both type of the users. However, it can be seen that the placement of the tablet is also affected by the handedness of the user. Moreover, it can be seen that the subjects tend to keep the tablet far from the user compared to the other objects. This can be due to the higher usability of the other four objects compared to the tablet in studying/ working environment.

In the study conducted for dining environment, there is no significant difference between the arrangement of the objects of both types of users except for the fact that they are almost equivalent mirror images of each other (except for the cup placement) [see Fig. 3.14. (b)]. This has occurred due to the handedness of the user. Both types of users have kept the plate in the middle. Spoon is kept adjacent to the plate at the side of their familiar hand. Mobile phone is kept at the side of unfamiliar hand. The cup is placed in the left hand side in the both instances. It is evident that the user tends to keep the phone by considering the fact that he/she might want to use it while having their meal. Therefore, they keep the phone at the side of the unfamiliar hand because the dominant hand gets occupied with the spoon. Moreover, users are cautious to keep the cup as far as possible to reduce the damages caused to mobile phone in an event of spilling the liquid of the cup all over the tray.

Fig. 3.15 to Fig. 3.24 depict the variations of the distances between the two objects in the above mentioned pairs. Dotted lines depict the average value of the distances of the respective pair. In the overall context, the lowest value for

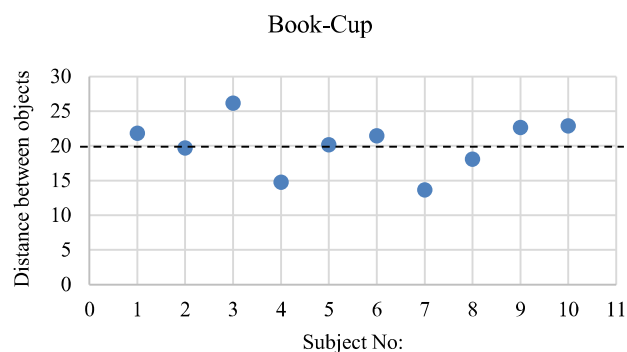


Figure 3.15: Book-Cup

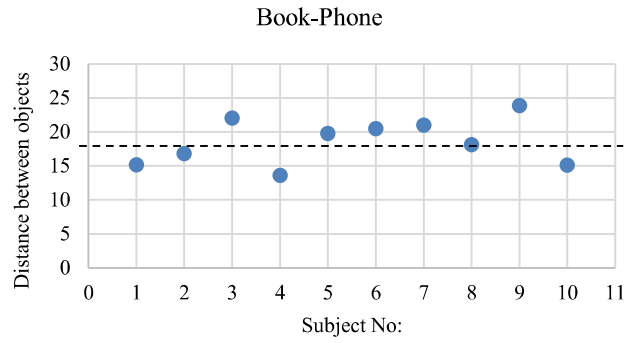


Figure 3.16: Book-Phone

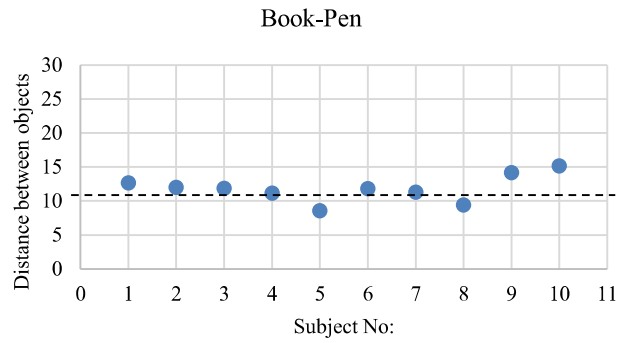


Figure 3.17: Book-Pen

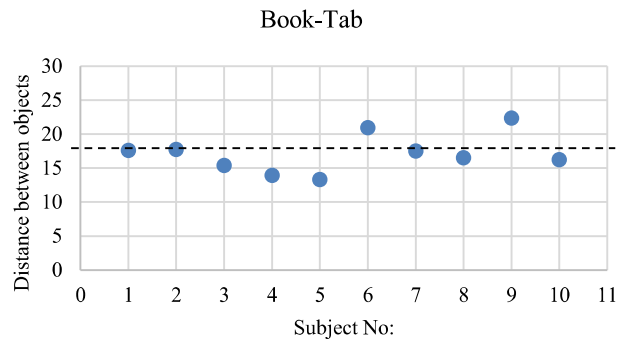


Figure 3.18: Book-Tab

the average distance is recorded for the pair: book-pen (10.9 cm). Users can consider various attributes of the objects when arranging the objects. However, it is evident that the users have given the usability of the two objects at the same instance, the highest precedence when placing object close to each other. Second lowest average value is recorded for plate-spoon pair (15.1 cm). Again, the usability of the two objects at the same instance has taken the precedence among the other attributes when keeping the objects close to each other.

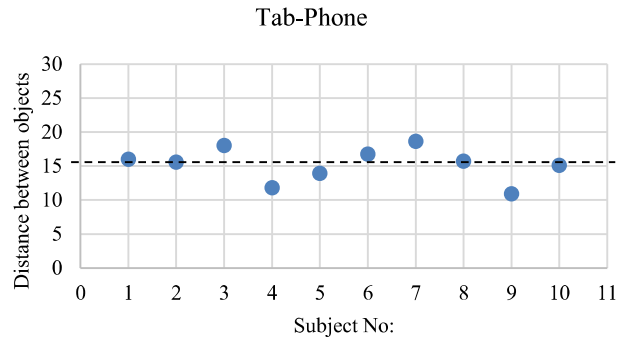


Figure 3.19: Tab-Phone

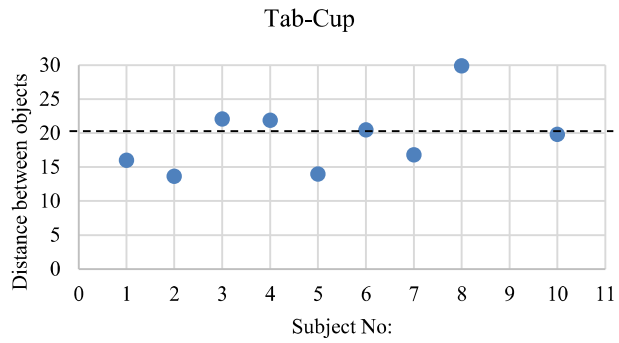


Figure 3.20: Tab-Cup

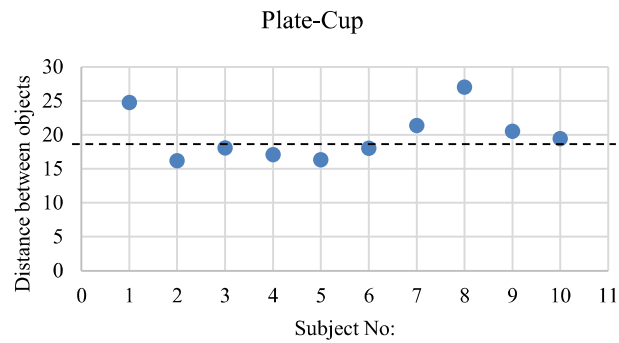


Figure 3.21: Plate-Cup

5 pairs have almost same average (approx: 20cm) value and they have the highest average distances among all the average values. Those pairs are book-cup, tab-cup, plate-cup, plate-phone and phone-cup. In those instances, it can be seen that the subjects have given the precedence to the safety of the electronic equipment. In all four pairs, electronic equipment can get damaged due to the spilling of liquids of the cup or the food items of the plate. Hence, subjects have tried to keep them as far as possible from each other.

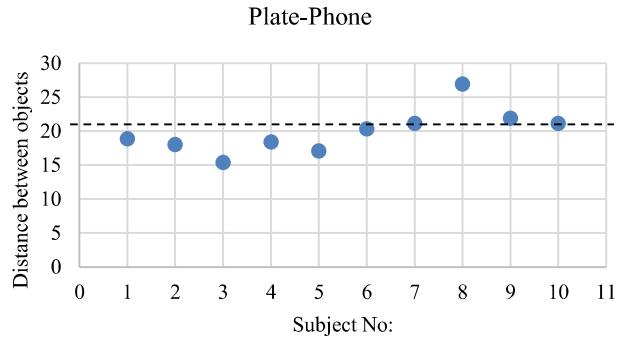


Figure 3.22: Plate-Phone

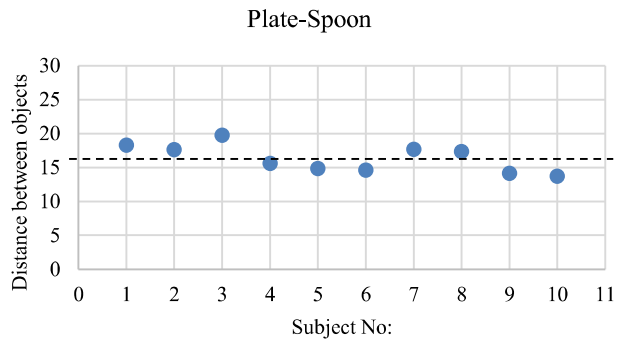


Figure 3.23: Plate-Spoon

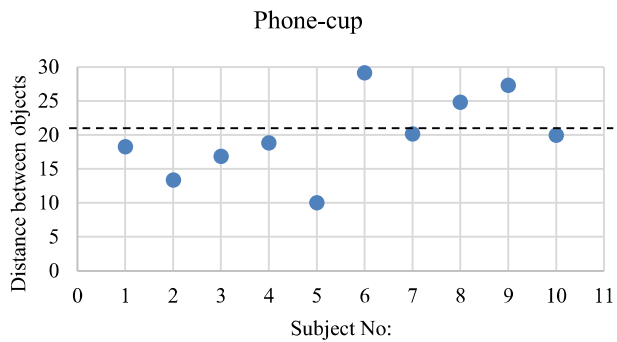


Figure 3.24: Phone-Cup

Phone-Tab pair depicts an average value (15.2 cm) close to the second lowest average value among all. Here, the subjects have considered the fact that those two objects have almost the same attributes. Hence, they tend to keep them as close as possible rather than keep them apart. Other pairs have displayed comparatively moderate mean distances. Objects in those pairs do not contain any highlighting allying or contrasting attributes towards each other. Hence users have not placed them in moderate distance from each other. Summary of

Table 3.2: Summary of the mean distances obtained for Object Pairs

| <b>Pair</b>   | <b>Mean Distance (cm)</b> |
|---------------|---------------------------|
| Book - Cup    | 20.12                     |
| Book - Phone  | 18.59                     |
| Book - Pen    | 11.80                     |
| Book -Tab     | 17.16                     |
| Tab - Phone   | 15.24                     |
| Tab - Cup     | 20.76                     |
| Plate - Cup   | 19.87                     |
| Plate - Phone | 19.91                     |
| Plate - Spoon | 16.40                     |
| Phone - Cup   | 19.86                     |

the mean distances obtained for object pairs is depicted in Table 3.2.

Following facts were revealed from the human study for the intelligent object manipulation and were used in the implementation described in Chapter 4.

- Incorporation of user preference and previous experience to object manipulation
- Possible locations for the object placements depending on the situation
  - Locations for placing objects according to the situations (Dining / Working) and the user handedness - Centroids of the clusters
- Preferred distance between two objects according to user preferences and past experience

## CHAPTER 4

# IMPLEMENTATION

Whole system was implemented inside the CoppeliaSim simulation environment. In order to achieve that working 3D model of the wheelchair was imported after converting it to Unified Robotic Description Format (URDF) model while defining the joint axes of the wheelchairs manually according to the original wheelchair motions. For this purpose SW2URDF add-in was used.

Other components such as Kinova Jaco 2 manipulator, tables, cups, etc were taken out from the CoppeliaSim inbuilt models. Fig 4.1 depicts the screen capture of the simulation environment.

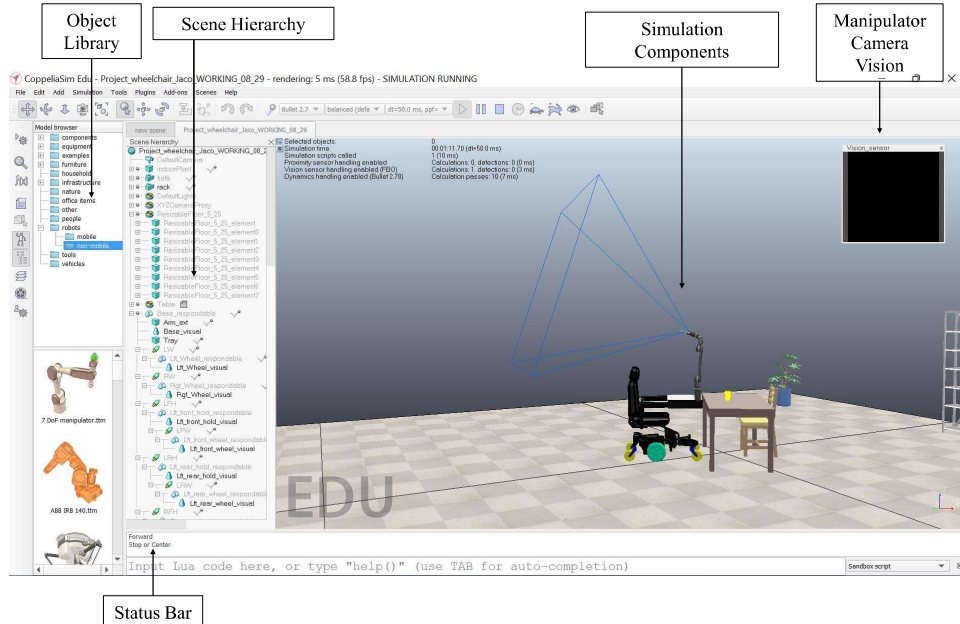


Figure 4.1: Screen Capture of the Simulation Environment

## 4.1 Overview of the Simulation

As mentioned in the section 3.2, the same EMG based controller with several modifications is implemented in the simulation. In order to carry out the object manipulation tasks few other EMG based controlling steps are added to the simulation. Fig. 4.2 shows the overview of the simulation. Since, the system is preset according to the handedness of the user and it is not done by the user, that step is not included in the Fig. 4.2.

Navigation of the wheelchair is done through the EMG based navigation algorithm. After the intention detection for the need of manipulator stage is reached, the manipulator begins to move in a horizontal straight line facing the possible region of the object that is going to be picked by the manipulator. The camera mounted on the gripper of the manipulator detects the red marker placed on the object and the manipulator stops at that point. Then the gripper moves in a straight line in the direction of the red marker until it reaches close to the object. The Sonar mounted on the detects the distance between the object and the gripper. Once it reaches the 10mm mark the gripper the motion of the manipulator is stopped. Then the user can use his/her biceps to rotate the gripper so that it could be in the desirable orientation to grasp the object. Once it is reached to the desired orientation user has to perform a task switcher in order to initiate the picking and placing of the object in the relevant location. In order to avoid the collisions and potential spatial ambiguities in placing the objects objects are placed sequentially. After manipulator retracts to its neutral position the same process will be restarted to pick the next object starting with the navigation stage. More details regarding the how the kinematic and spatial challenges are met by the proposed system will be discussed in the upcoming sections and subsections.



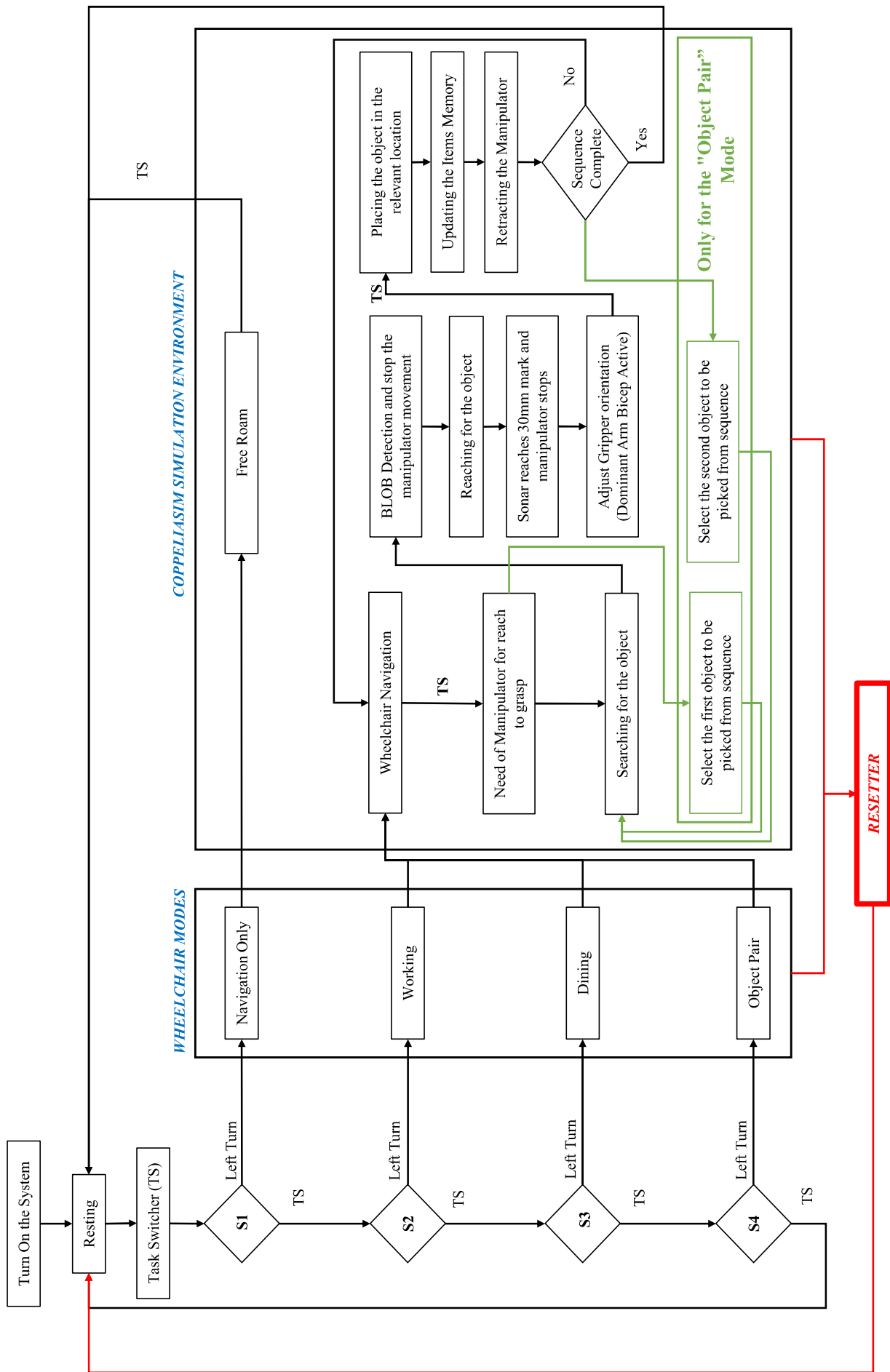


Figure 4.2: Overview of the Simulation

### 4.1.1 Navigation in the Simulation Environment

As mentioned previously, the 3D model built in SOLIDWORKS is imported to CoppeliaSim environment after converting it to URDF model. However, the imported model would not work unless the dynamic properties of the wheelchair are not set and balanced according to the real life properties. To set the dynamic properties for each and every individual dynamic component of the simulation

**Rigid Body Dynamic Properties**

☒ Body is responsible

Local responsible mask: [1][0][0][0][0][0][0][0][0][0]

Global responsible mask: [1][1][1][1][1][1][1][1]

Edit material

Apply to selection

☒ Body is dynamic

☐ Start in sleep mode ☒ Set to dynamic if gets parent

Compute mass & inertia properties for selected convex shapes

Mass

Mass [kg]: 4.139e+01

M=M\*2 (for selection)

M=M/2 (for selection)

Principal moments of inertia / mass

X [m^2]: 1.251e-01

Y [m^2]: 3.520e-02

Z [m^2]: 1.237e-01

I=I\*2 (for selection)

I=I/2 (for selection)

Pos./orient. of inertia frame & COM relative to shape frame

X [m]: -1.397e-02

Y [m]: -9.912e-03

Z [m]: -1.074e-02

Alpha [deg]: -9.01e+01

Beta [deg]: -1.36e+01

Gamma [deg]: +1.78e+02

Set inertia matrix and COM relative to absolute frame

Apply to selection

Figure 4.3: Rigid Body Dynamic Properties Dialog

“Rigid Body Dynamic Properties” dialog is used (see Fig. 4.3). In order to generate the simulation with dynamic properties, “bullet 2.7 engine” is used in this research.

Using this dialog, mass and inertia properties are calculated for the imported objects. However, this step is not necessary for the objects that are imported from the CoppeliaSim library. Moreover, for every component it is required to set whether they are static or dynamic.

After, making the working dynamic model of the wheelchair inside the CoppeliaSim Environment, CoppeliaSim and MATLAB are interfaced through a “Re-

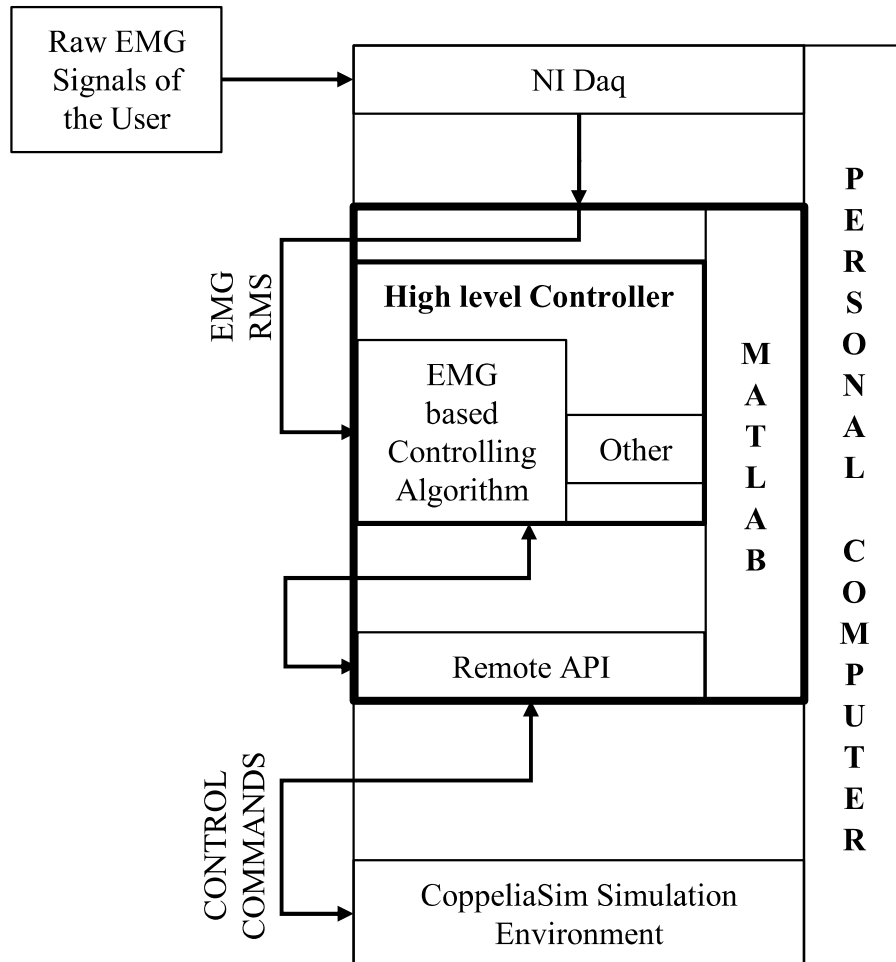


Figure 4.4: Interface between High level controller and CoppeliaSim Simulation

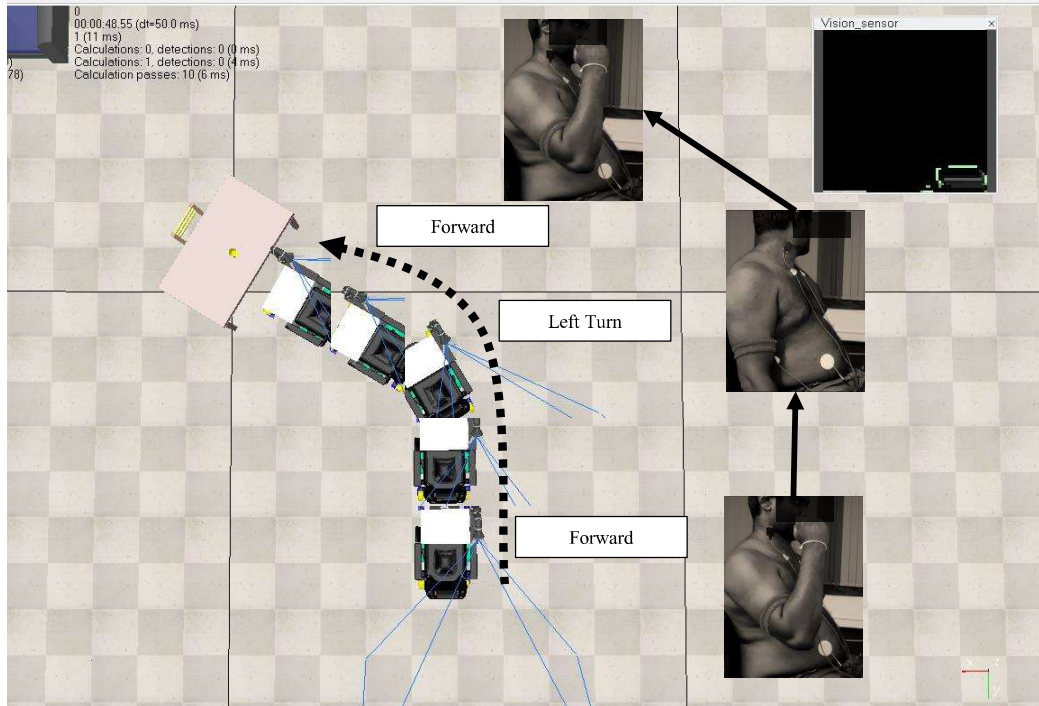


Figure 4.5: Traverse of the wheelchair to pick up an object: Wheelchair user gives the navigation commands through the EMG signals to wheelchair to reach towards the object. This path is not fixed and it depends on the user’s choices in giving navigation commands in relevant intervals. User’s actions to generate the required EMG inputs are also depicted in the figure.

note Application Priming Interface (Remote API)”. Through the Remote API, high level controller is able to send and receive the control commands with the Coppeliasim Simulation (see Fig. 4.4). The wheelchair built inside the Coppeliasim simulation environment has 2 active wheels and 4 passive wheels just as the original electric wheelchair. Two active wheels in the simulation are working in the assumption that they are connected through a differential drive.

For the navigation of the wheelchair, the EMG based navigation algorithm described in section 3.2 is used. By looking at the different views of the wheelchair location inside the simulation environment, user can get the vision feedback to reach the desired location of the simulation environment while avoiding the obstacles. Navigation corresponds to the stage 2 of the EMG based controlling algorithm described in section 3.2. A sample navigation done in the simulation environment is shown in the Fig. 4.5.

#### 4.1.2 Object Manipulation

Fig. 4.6 shows the wheelchair simulated inside the CoppeliaSim environment. It consists of a wheelchair manipulator: Kinova Jaco 2 and a wheelchair tray. Jaco arm is mounted on the arm stand extension of the wheelchair. Moreover, the wheelchair tray is also attached to the same extension of the arm stand. Wheelchair tray has the same dimensions ( $53\text{cm} \times 36\text{cm}$ ) as the wheelchair tray

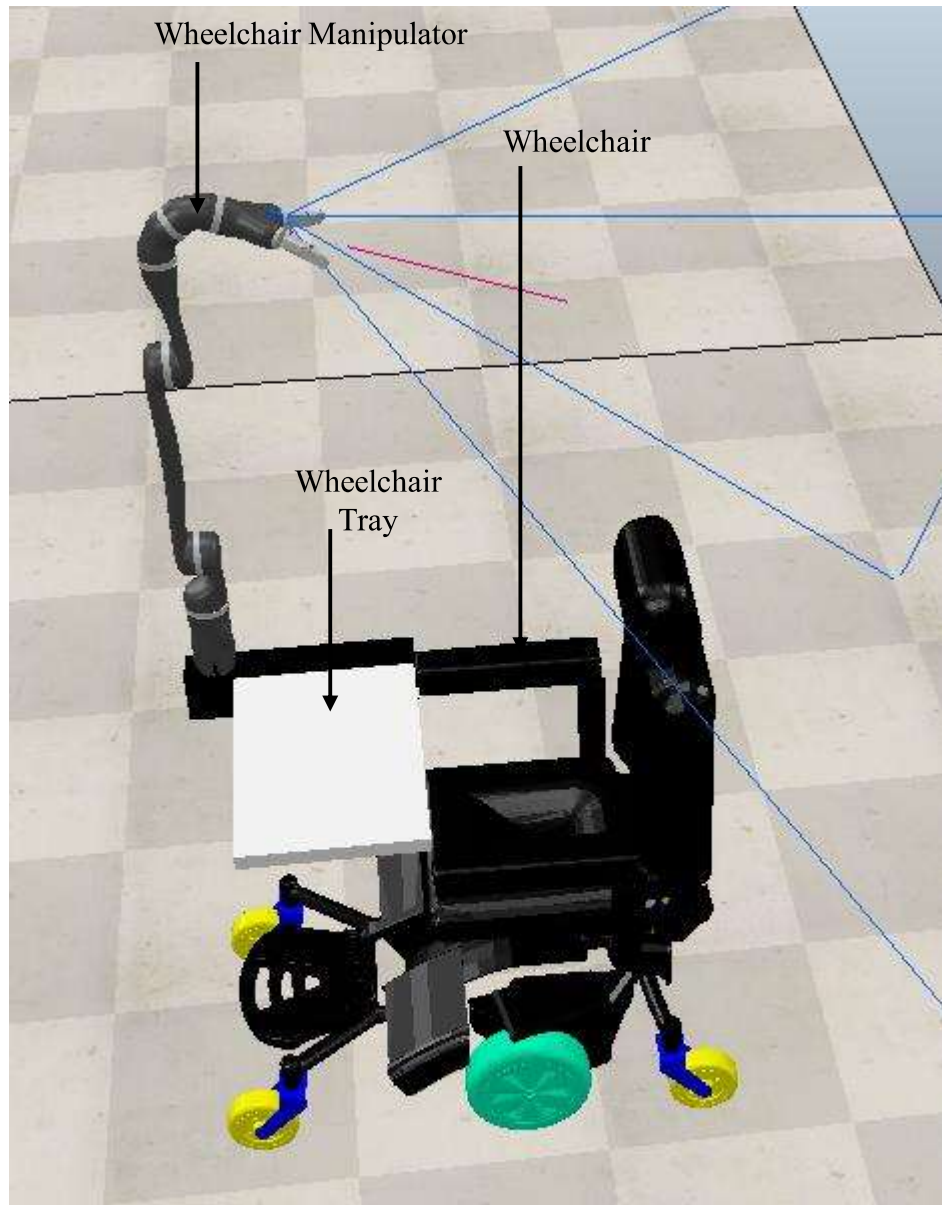


Figure 4.6: Wheelchair components

Table 4.1: Specification of Kinova Jaco 2 [187]

|                 |                                                                       |
|-----------------|-----------------------------------------------------------------------|
| Total Weight    | 5.2kg                                                                 |
| Reach           | 90cm                                                                  |
| Maximum Payload | 1.6 kg (mid-range continuous)<br>1.3 kg (full-reach peak / temporary) |

used for the human study described in subsection 3.3.1.

Wheelchair manipulator specifications are mentioned in the Table 4.1 [187]. Since, other specifications are irrelevant for the simulation they are not mentioned in the table.

In this research object manipulation consists of 6 processes. Each of them serves a specific purpose and works as a chain of commands (see Fig. 4.7).

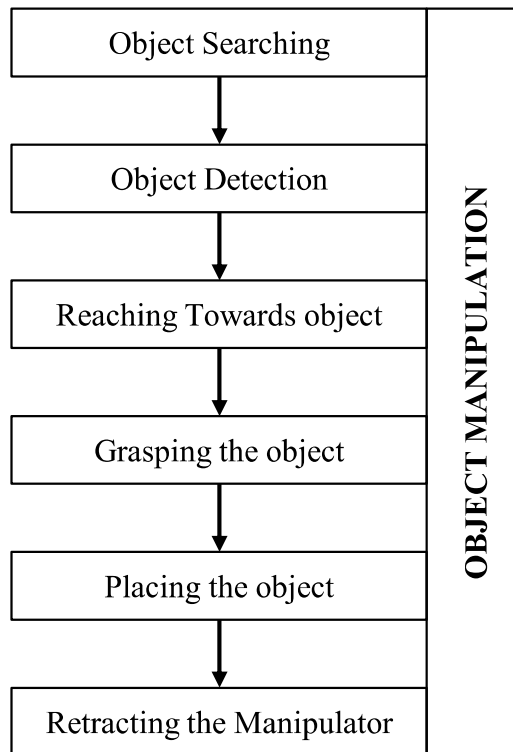


Figure 4.7: Processes involved in Object Manipulation

## Object Searching and detection

In this research an eye in the hand configuration of a camera is used. Here the camera is mounted on the gripper in order to get the vision feedback. Along with the camera a ray type proximity sensor (sonar) is also attached to the gripper (see Fig. 4.8).

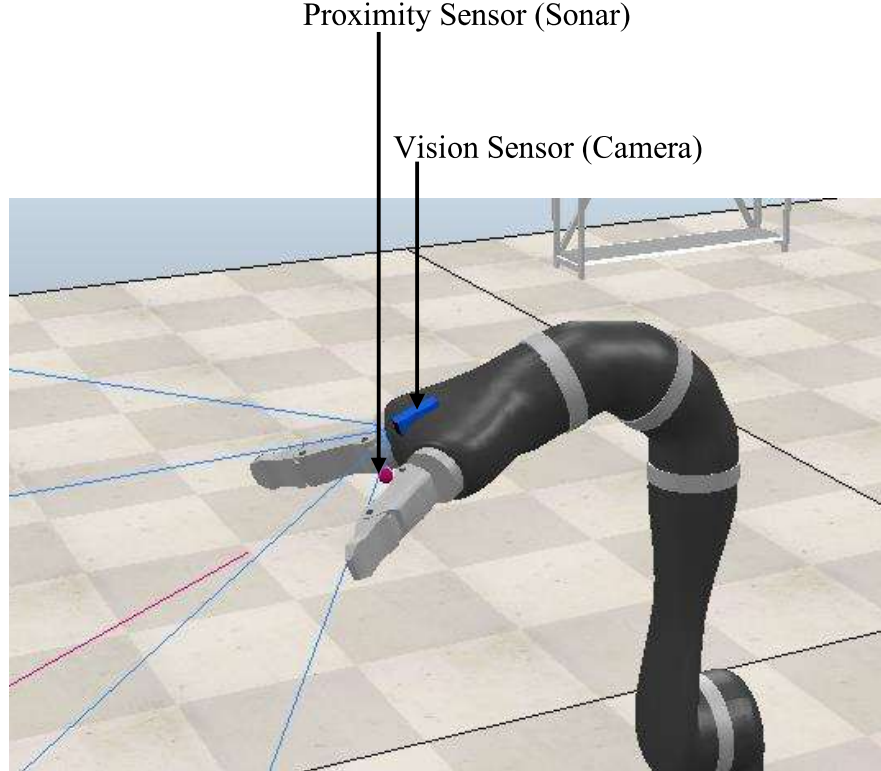


Figure 4.8: Sensor Placement on the Gripper

To search for the object robot gripper moves from point  $P_{int}(X,Y,Z)$  to point  $P_{final}(X_f,Y_f,Z_f)$  in a straight line (see Fig. 4.9) with respect to the base frame of Jaco 2. Since,  $P_{int} P_{final}$  line is parallel to the X axis of the base frame of the manipulator,  $P_{final}$  can be calculated as equation 4.1.

$$(X_f, Y_f, Z_f) = (X + 25, Y, Z) \quad (4.1)$$

Gripper pose at  $P_{int} (X,Y,Z)$  is calculated using the homogeneous transfor-



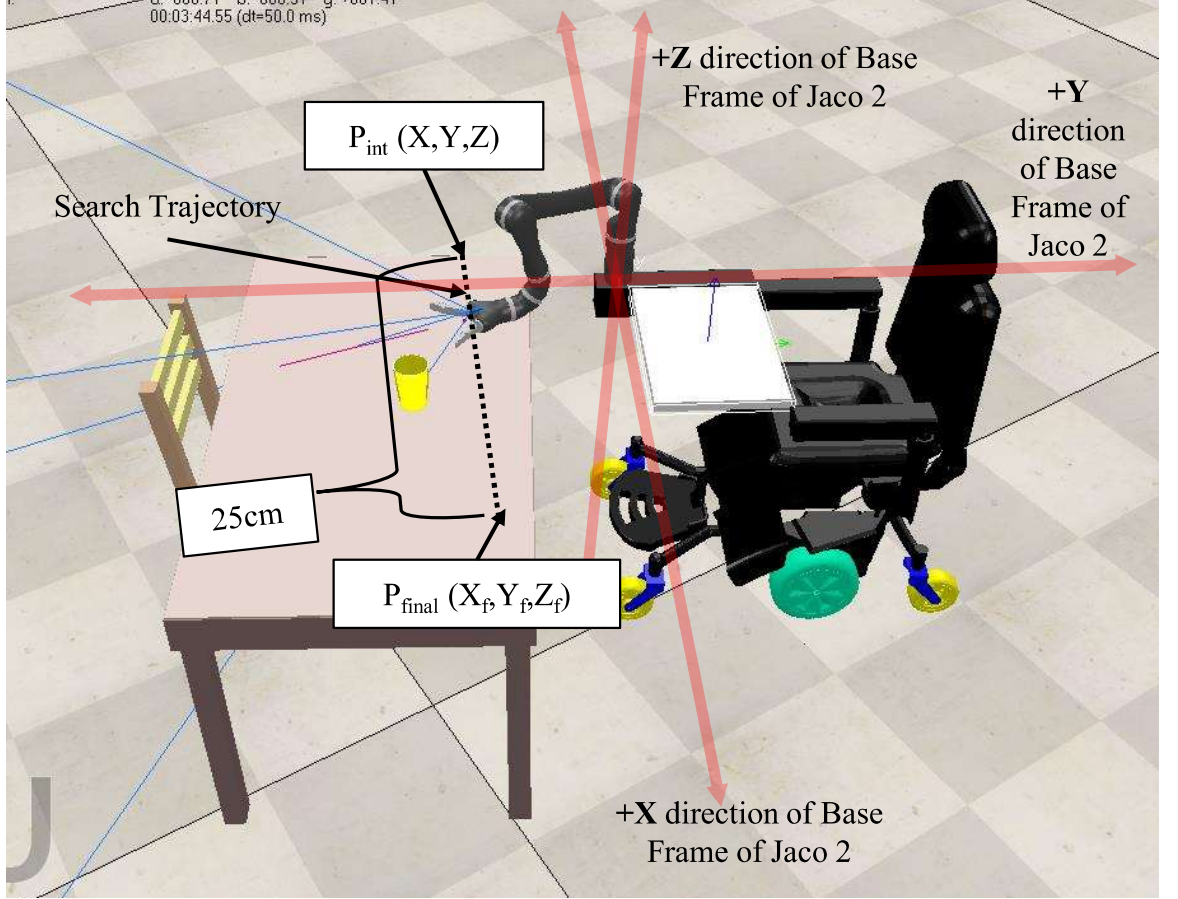


Figure 4.9: Search Trajectory and the base frame assignment of Jaco 2

mation of the Jaco 2. In order to calculate the gripper pose, kinematic model depicted in Fig. 4.10, the Denevit Hartenberg (DH) parameters depicted in Table 4.2 and equation 4.2 are used. Since Peter Corke's robotic toolbox uses the classical DH parameters, Table 4.2 depicts the classical DH parameters of Kinova Jaco 2.

$${}^0_6T = {}^0_1T \times {}^1_2T \times {}^2_3T \times \dots \times {}^5_6T \quad (4.2)$$



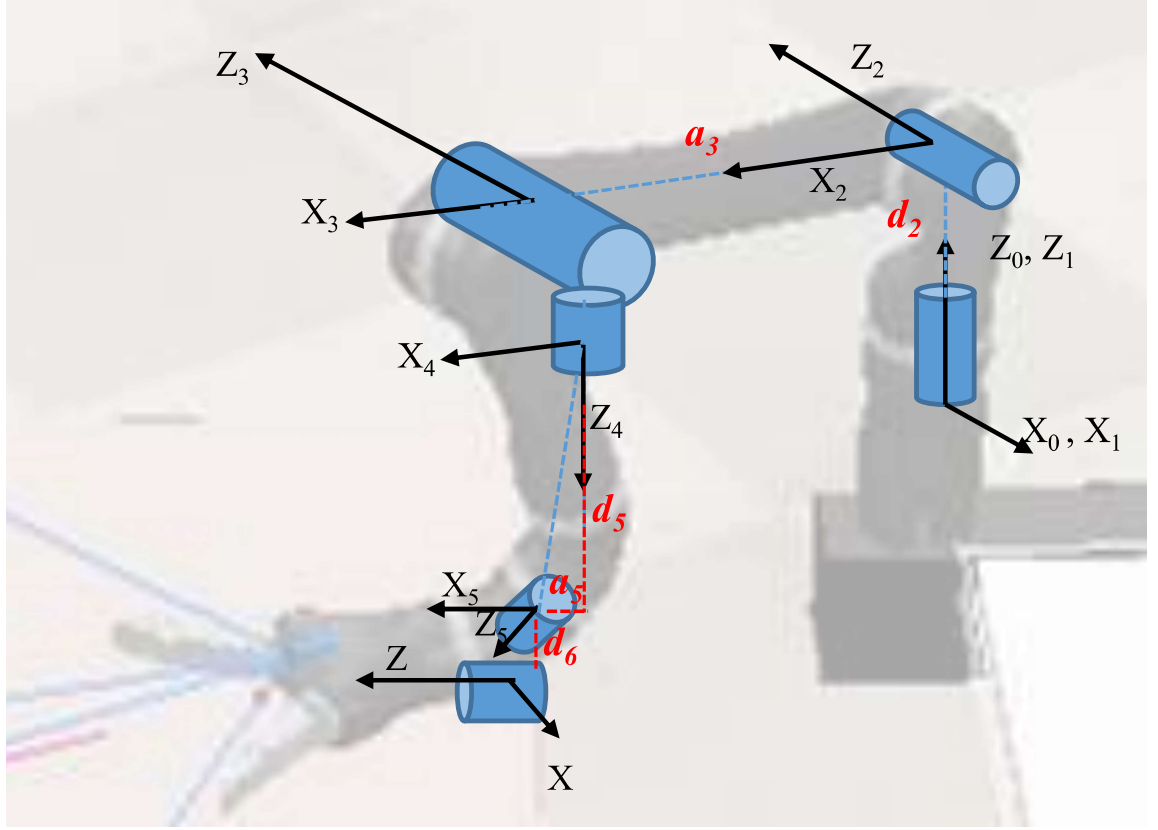


Figure 4.10: Kinematic Model of the Kinova Jaco 2

Here,  $d_2 = 7.05\text{cm}$ ,  $a_3 = 41\text{cm}$ ,  $d_5 = 27.15\text{cm}$ ,  $a_5 = 3.71\text{cm}$ ,  $d_6 = 6.41\text{cm}$  and  $d_7 = 10.00\text{cm}$ . In order to calculate the Homogenous Transformation from one joint  $i - 1$  to the next  $i$  Equation 4.3 is used Fig. shows the link model built for Jaco 2 inside the robotics toolbox.

Table 4.2: D-H parameters of Kinova Jaco 2

| Link | $\alpha_i$ | $\mathbf{a}_i$ | $\mathbf{d}_i$ | $\theta_i$          |
|------|------------|----------------|----------------|---------------------|
| 1    | 0          | 0              | 0              | $\theta_1$          |
| 2    | $\pi/2$    | 0              | $d_2$          | $\theta_2$          |
| 3    | 0          | $a_3$          | 0              | $\theta_3$          |
| 4    | $\pi/2$    | 0              | 0              | $\theta_4$          |
| 5    | 0          | $a_5$          | $d_5$          | $\theta_5$          |
| 6    | $\pi/2$    | 0              | $d_6$          | $-\pi/2 + \theta_6$ |

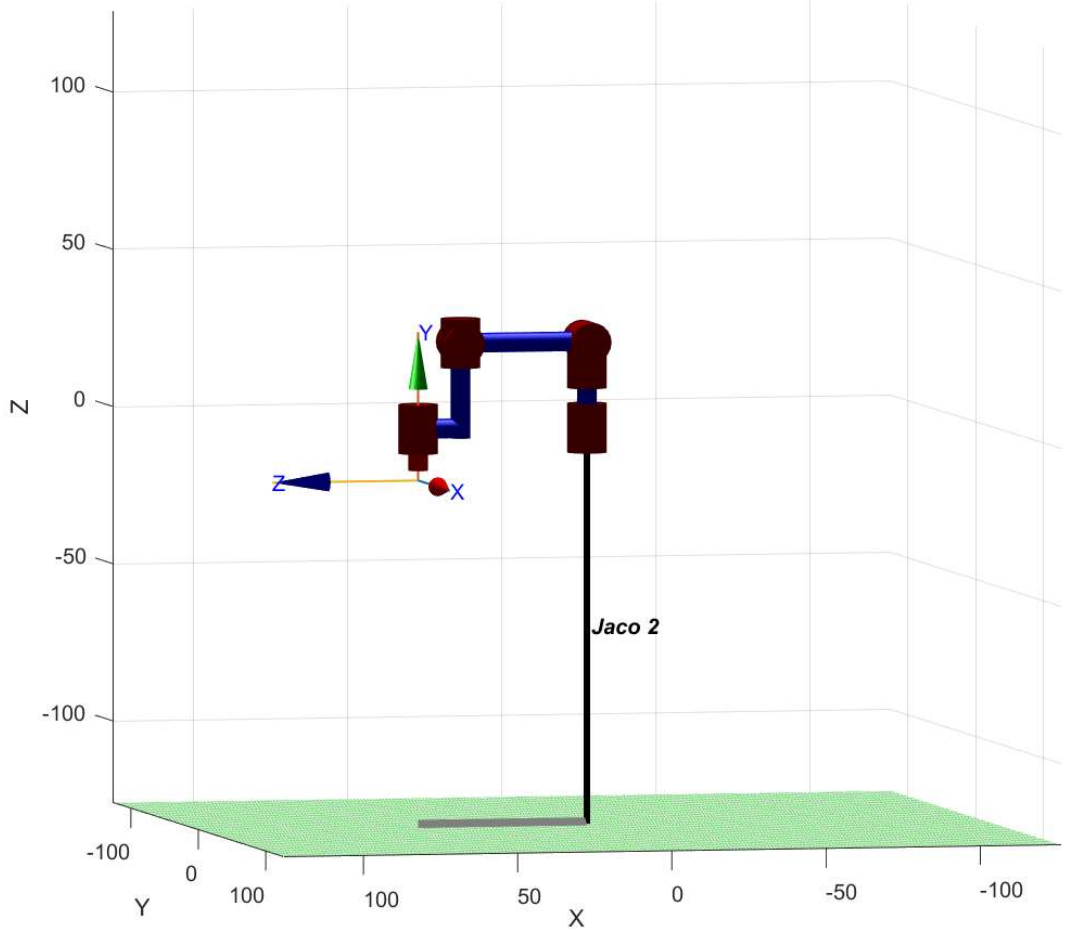


Figure 4.11: Link model built in the robotics toolbox

$${}^i T = \begin{bmatrix} \cos\theta_i - \sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i \\ 0 & \sin\alpha_i & \cos\alpha_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.3)$$

Here the joint angles are manually set so that initially the gripper is in the pose  $P_{int}$  [see Fig. 4.9]. In order to move the gripper from the  $P_{int}$  to  $P_{final}$ , “ctrj” function of the MATLAB robotics toolbox [188] is used. This function generates a straight path connecting the poses. The path generated is not continuous. Here the path is divided in to 20 points to make a smooth movement of the gripper along the path. For each point, inverse kinematic solution is computed through

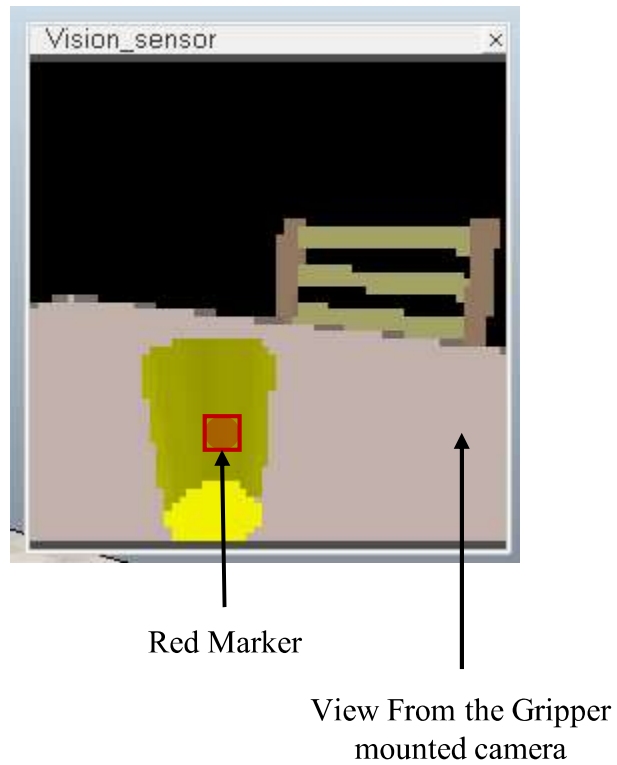


Figure 4.12: BLOB Detection

robotics toolbox to generate the relevant joint angles according to the gripper pose.

Gripper camera is used to detect the red marker placed on the object just as described in the previous human study (see Fig. 4.12). Once the binary large object (BLOB) / red marker is detected, gripper movement stops.

## Reaching towards the object

After the brief stopping at the BLOB detection, the gripper starts to move towards the object using the “ctrj” function of the MATLAB robotics toolbox. To calculate the expected final pose of the gripper after starting to move towards object, equation 4.4 is used.

$${}_{Base}^{Final}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & D_{exp} \\ 0 & 0 & 0 & 1 \end{bmatrix} \times {}_{Base}^{Current}T \quad (4.4)$$

Here,  $D_{exp}$  is the expected distance from the stopping point to the object.  $D_{exp}$  is set to 20cm so that manipulator may not achieve singularity due to its maximum reach. When the gripper is in the close proximity of the object the gripper movement is set to stop when the sonar reaches 3cm mark.

## Grasping the object

Once the gripper movement is stopped after the sonar reading, gripper gripper rotation is enabled. This feature is added to the system to compensate the misalignments of the orientation of the gripper with the required pose for the grasping. In order to do that, biceps activation is used. Activation of the left biceps brachii will enable the clockwise rotation of the gripper whereas the activation of the right biceps brachii will enable the clockwise rotation of the gripper. User has to intent to flex their respective elbows in order to activate the relevant biceps brachii.

When the required gripper orientation is achieved, user has to perform a task switcher to finish adjusting the gripper and to enable the grasping motion.

## Placing the Object

Object placing is a complicated task as it requires to consider not only the locations of placements but also the collisions that could occur between the objects. In order to avoid those spatial ambiguities a sequential placement method is used in this research. Moreover, this research considers three object placement occasions: two situation based object placements (dining/ working) and placing objects in pairs. In dining environment objects are placed in the order of plate→spoon→cup→phone whereas in working environment the order would be book→pen→phone→tab→cup. After placing one object, again the whole process should be repeated to place the next object starting from the wheelchair navigation stage [see Fig.4.2]. When the sequence is completed system will be set to its default starting stage where it checks the task which is intended by the user.

The remaining object placement scenario is achieved in the following way. Since it considers the object placements in pairs the first object that is placed by the manipulator is placed at the  $P_1$  position (see Fig. 4.13). The location for the second object is determined as a point that lies on the line (dotted red line in Fig. 4.13) which connects the  $P_1$  and the upper most right corner of the wheelchair tray.

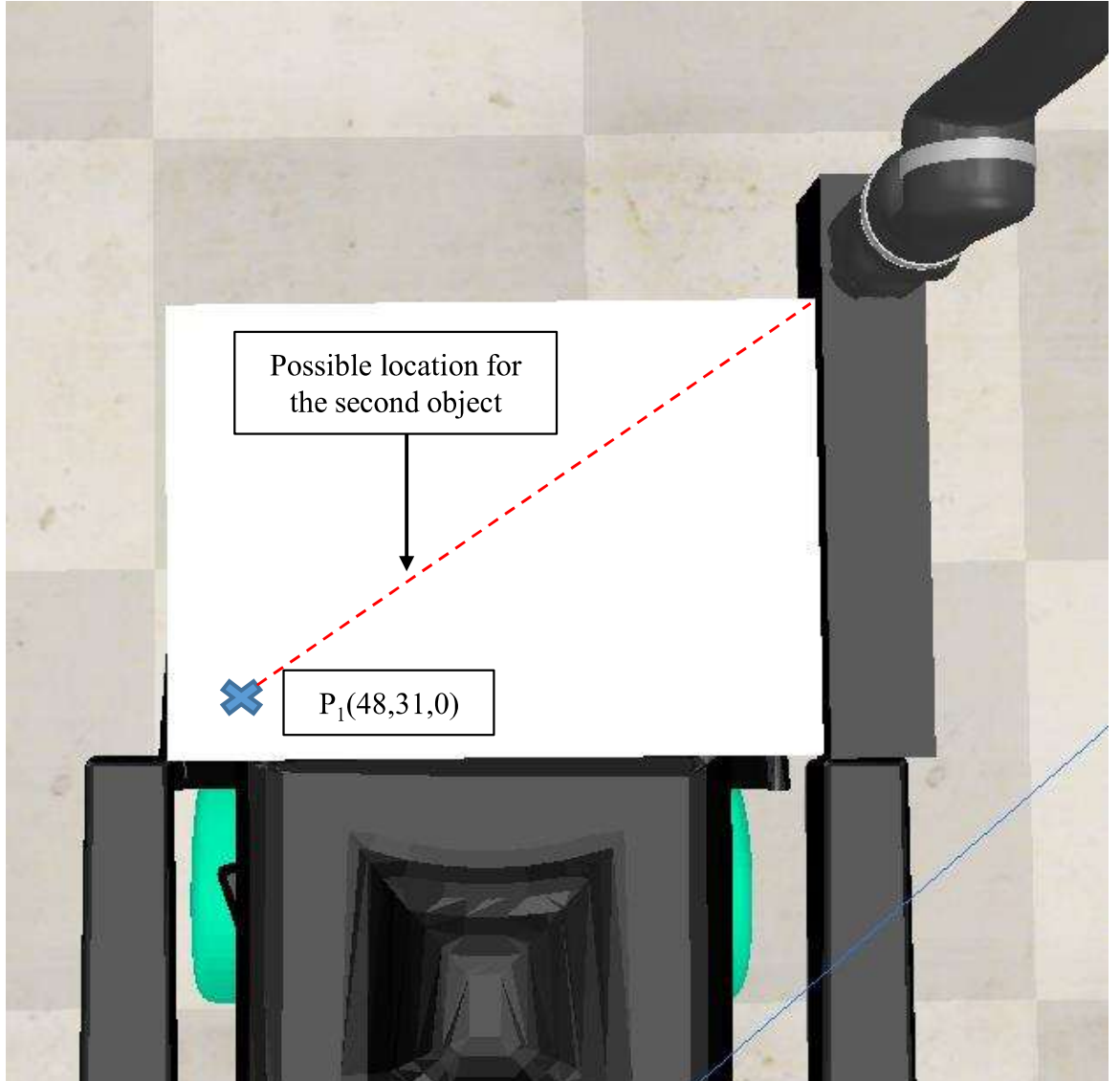


Figure 4.13: Object placing in pairs

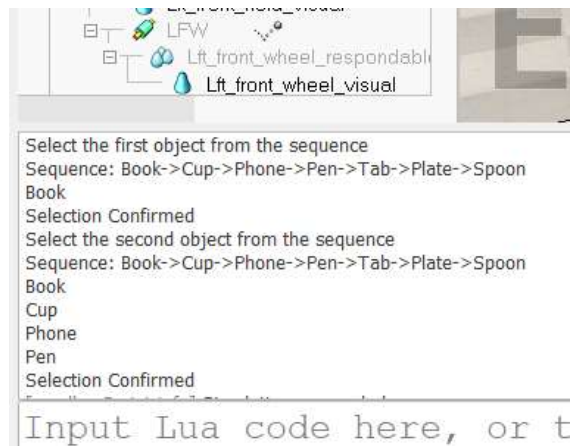
The gripper pose for the second object is calculated using the values in Fig. 4.14, the simple coordinate geometry and equation 4.4. Once, the second object placing pose of the gripper is calculated, using the “ikine” command of MATLAB robotics toolbox the joint angles for the second pose of the manipulator are calculated. Jaco 2 can then follow the object picking process and place the object in the calculated location as the joint angle values of the Jaco 2 are now available for the second location.

Here the first object is placed without considering the object attributes or user

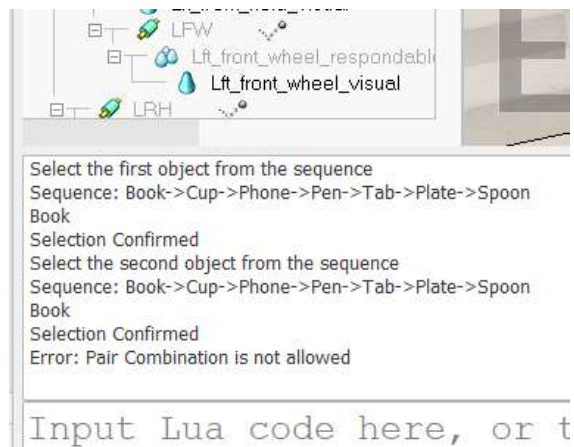
|              | <i>Book</i> | <i>Cup</i> | <i>Phone</i> | <i>Pen</i> | <i>Tab</i> | <i>Plate</i> | <i>Spoon</i> |
|--------------|-------------|------------|--------------|------------|------------|--------------|--------------|
| <i>Book</i>  | Error       | 20.12      | 18.59        | 11.80      | 17.16      | Error        | Error        |
| <i>Cup</i>   | 20.12       | Error      | 19.86        | Error      | 20.76      | 19.87        | Error        |
| <i>Phone</i> | 18.59       | 19.86      | Error        | Error      | 15.24      | 19.91        | Error        |
| <i>Pen</i>   | 11.80       | Error      | Error        | Error      | Error      | Error        | Error        |
| <i>Tab</i>   | 17.16       | 20.76      | 15.24        | Error      | Error      | Error        | Error        |
| <i>Plate</i> | Error       | 19.87      | 19.91        | Error      | Error      | Error        | 16.40        |
| <i>Spoon</i> | Error       | Error      | Error        | Error      | Error      | 16.40        | Error        |

Figure 4.14: Allowed combinations in placing objects in pairs (all the values are in cm)

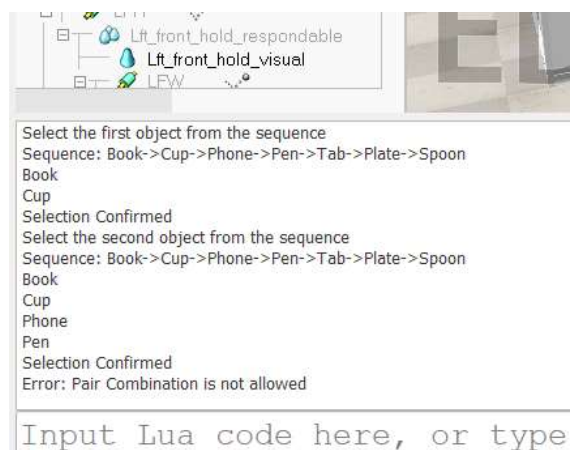
preference. Once the object is placed, user has to activate his right bicep until the placed object is shown in the status bar. Objects are stored in a sequence of 7. Sequence is as follows. Book → Cup → Phone → Pen → Tab → Plate → Spoon. Once the required object is reached user has to confirm his selection by performing a task switcher. Once the object is confirmed system would ask (a message will be displayed in the status bar) “Select the next second object from the sequence”. Again user has to confirm his selection as he/she did for the first object. If the object pair is not in accordance with the combinations in Fig. 4.14, it will display an error. Once the second object is confirmed the object



(a)



(b)



(c)

Figure 4.15: Example of command sequence in placing objects in pairs: (a). Successful placements (b). Same object cannot be selected twice (c). Another restricted combination



picking process will be continued and the object will be placed at the calculated second position. Example for successful placement and selections of restricted pairs are depicted in the Fig.4.15 . Here the screen captures of the status bar of the simulation are taken to show the command sequence.

***Intermediate Position:-*** Here the intermediate position refers to the position that the robot manipulator reaches before placing the object (see Fig. 4.16). This position is located directly above the middle of the wheelchair tray and the pose of the manipulator at that position is predefined. Hence, using the “jtraj” command of the MATLAB Robotics toolbox, the trajectory from the picking location to the intermediate position and the trajectory from the intermediate location to the placing location can be generated.

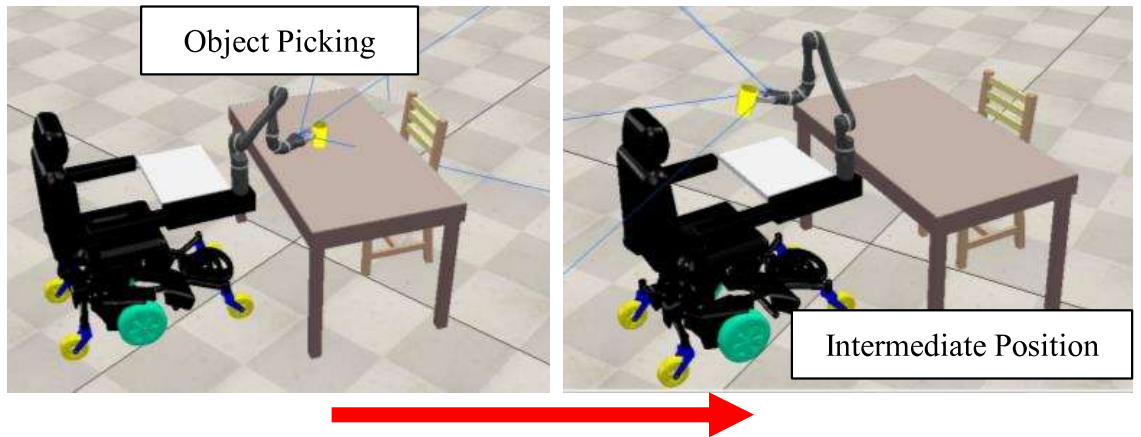


Figure 4.16: Intermediate Position of the manipulator

## Retraction of Robot Arm

Retraction of the manipulator to its neutral position finishes the object placement task for one object. Then it will also initiate the wheelchair motion to go to the location of the next object. If all the objects of the intended task have been placed on the wheelchair tray, system will latch on to its default initial stage of resting.

### 4.1.3 Reset Command (Resetter)

Reset command or Resetter is added to the system as a safety mechanism. If the user performs a resetter at any point of the tasks system will pause. It is performed by performing task switcher and right rotation of the head at the same time (see 4.17). If the Resetter is performed in the middle of a manipulator task, manipulator will stop/freeze at the configuration it was at when the Resetter is performed. If another Resetter is performed system will continue where it was left off. However, if a task switcher is performed instead of the consecutive Resetter system will latch on to its default Resting stage unless the system was paused at a manipulator operation. If it was stopped at a manipulator operation where it

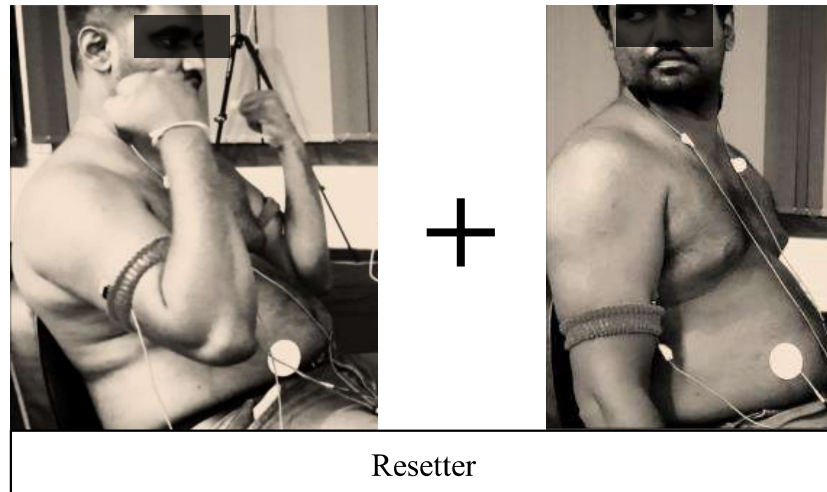


Figure 4.17: Resetter

holds an object in its gripper and the user wants to start he may have to ask for external care giver's help to remove the object from the gripper.

An example of the detailed process flow of the object manipulation in working mode is depicted in the Fig. 4.18, Fig. 4.19 and Fig. 4.20. It is apparent that the proposed is not fully automatic. It needs the user input through the EMG signals to carry out the whole process. Hence the system can be considered as a Human in the loop (HITL) system where the user feedback decides the key aspects of the proposed system.

| Precedence Number | Available options                             | Selected Option                      | User Activity Required for the selection                                                                                                                                              |
|-------------------|-----------------------------------------------|--------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1                 | Turn on the system (Turn on the system)       | N/A                                  | N/A                                                                                                                                                                                   |
| 2                 | Task Switcher                                 | Task Switcher                        | <br>x 1                                                                                              |
| 3                 | Navigation Only/ Working/ Dining/ Object Pair | Working                              | <br>x 2<br><br>x 1 |
| 4                 | Wheelchair Navigation                         | Navigate towards the required object |                                                                                                     |

Figure 4.18: Activities involved in the working mode. (Rest of the activities is continued in Fig.4.19 and Fig. 4.20 )

|    |                                                          |                                                          |                                                                                         |
|----|----------------------------------------------------------|----------------------------------------------------------|-----------------------------------------------------------------------------------------|
| 5  | Task Switcher                                            | Task Switcher                                            |  x 1   |
| 6  | Intention to use the manipulator                         | Intention to use the manipulator                         |  x 1   |
| 7  | Searching for the object                                 | N/A                                                      | N/A                                                                                     |
| 8  | Detecting and reaching                                   | N/A                                                      | N/A                                                                                     |
| 9  | Adjusting the pose of the gripper                        | Adjusting the pose of the gripper                        |  x 1  |
| 10 | Task Switcher                                            | Task Switcher                                            |  x 1 |
| 11 | Grasping and placing the object in the relevant location | Grasping and placing the object in the relevant location | N/A                                                                                     |

Figure 4.19: Activities involved in the working mode. (Rest of the activities is continued in Fig.4.20 )

|    |                                                                                       |     |     |
|----|---------------------------------------------------------------------------------------|-----|-----|
| 12 | Retraction of the manipulator                                                         | N/A | N/A |
| 13 | Repetition of the process from “4” to “12” until all 5 objects are placed on the tray | N/A | N/A |
| 14 | Resting (Latch on to “1”)                                                             | N/A | N/A |

Figure 4.20: Remaining activities involved in the working mode.

#### 4.1.4 Simulation Results

Object arrangement in the three tasks were compared and contrasted with the results obtained from the human study. In order to do so, experiments were carried out with 4 healthy subjects. Three of them were right handed users whereas the other user was left handed. Since the object placement area is a limited space and there are considerable differences between the simulation environment and the actual scenario, only the patterns after the object arrangement are compared for the dining and working environments. For the task of placing the objects in pairs distance between the centres of the two objects were measured using the Kinovea software [189]. In each occasion a screen capture of the ortho-graphic view of the wheelchair tray was taken. All four users were able to perform the tasks after getting familiar with the proposed intelligent object manipulation algorithm.

Fig. 4.21 to Fig. 4.24 depict the results obtained from the simulation environment for the situation based object placements. In all of the arrangements it

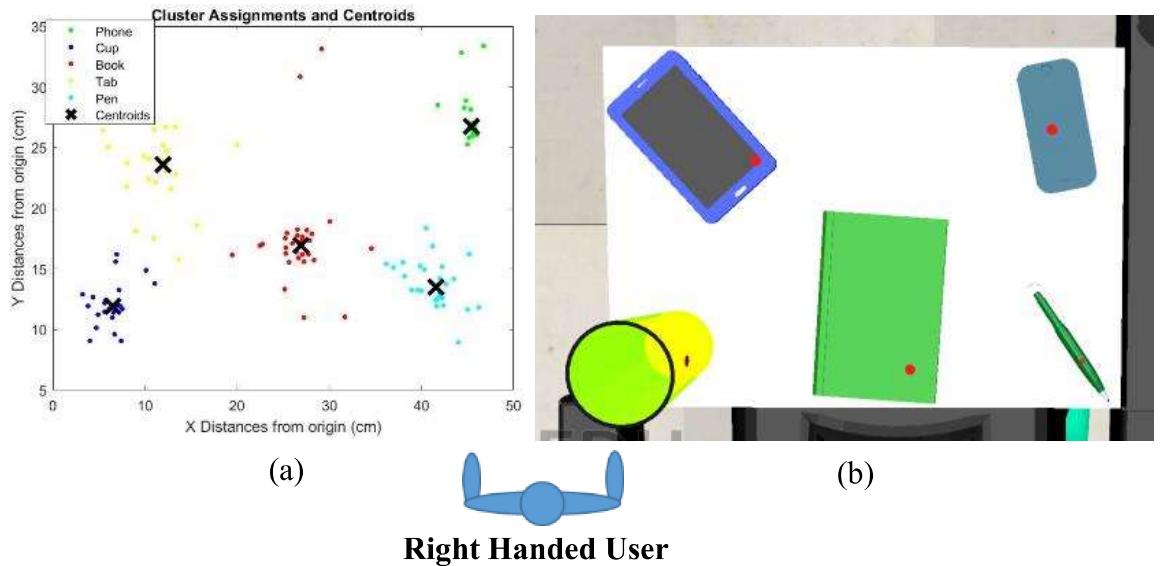


Figure 4.21: Working arrangement of objects for right handed user : (a) Obtained results from Human Study (b) Object arrangement done in the simulation environment

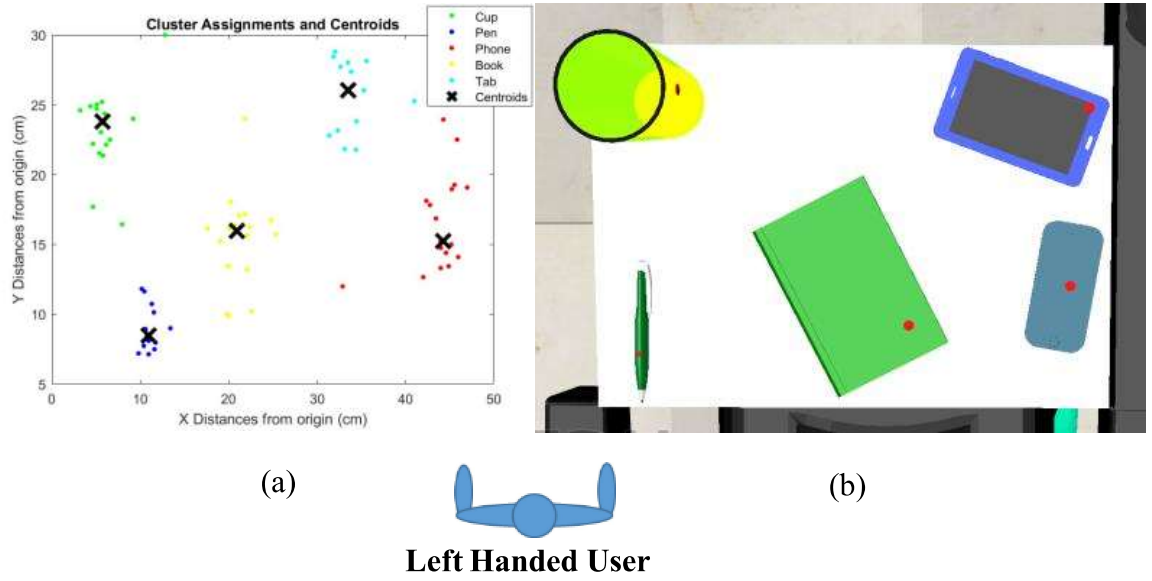


Figure 4.22: Working arrangement of objects for left handed user : (a) Obtained results from Human Study (b) Object arrangement done in the simulation environment

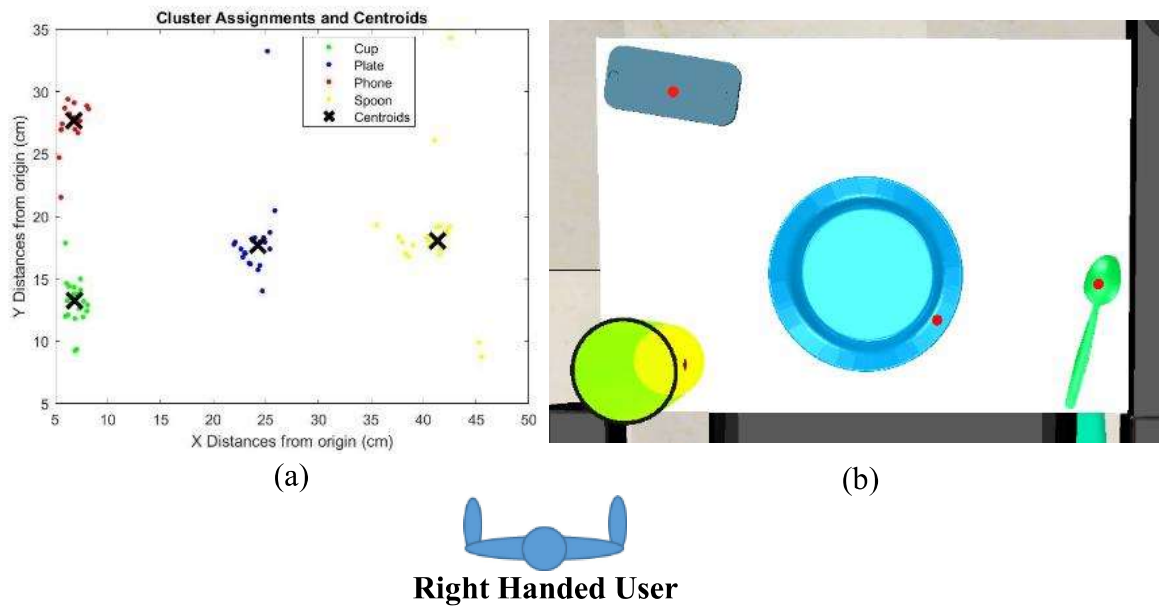


Figure 4.23: Dining arrangement of objects for right handed user : (a) Obtained results from Human Study (b) Object arrangement done in the simulation environment

can be seen that they have secured the patterns depicted by the object clusters. Moreover, it can be seen that even in the same situation orientation of the objects are not the same. Orientation for the picking/grasping of the object is adjusted



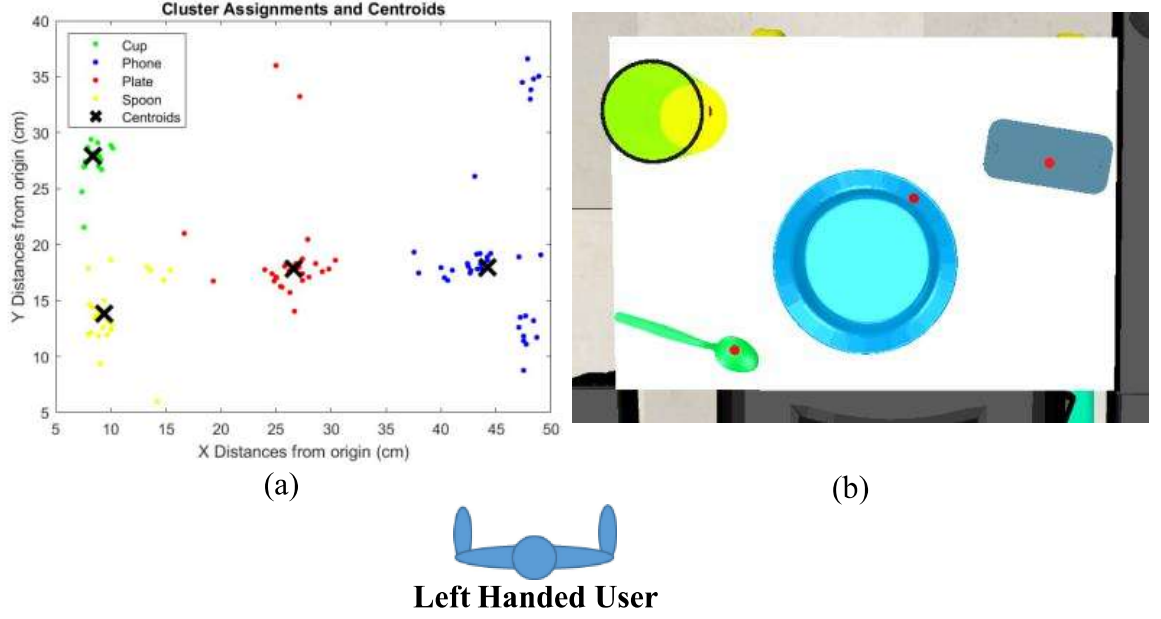


Figure 4.24: Dining arrangement of objects for left handed user : (a) Obtained results from Human Study (b) Object arrangement done in the simulation environment

manually by the user according to his/her preference after the manipulator is stopped by the sonar reading. Hence, the location where the object is grasped can be varied according to the user's state of mind at the particular moment. Due to the divergent nature of the grasping stage, different orientation may be occurred for the placed object for different trials. However, this scenario does not affect the final pose of the manipulator when placing the object as it is independent of the pose of grasping of the object. Therefore, the location of placing of the object would not change and it would only be changed if the handedness of the user is changed.

Fig. 4.25 depicts the object placements done in pairs in the simulation environment. These pairs were placed under the constraints mentioned in Fig. 4.14. Even though the object placement pattern was paramount rather than the individual object locations in the previous experiment, individual object location is very important for this experiment. Specially the object location of the second object plays a vital role as it defines the distance between the two objects. The

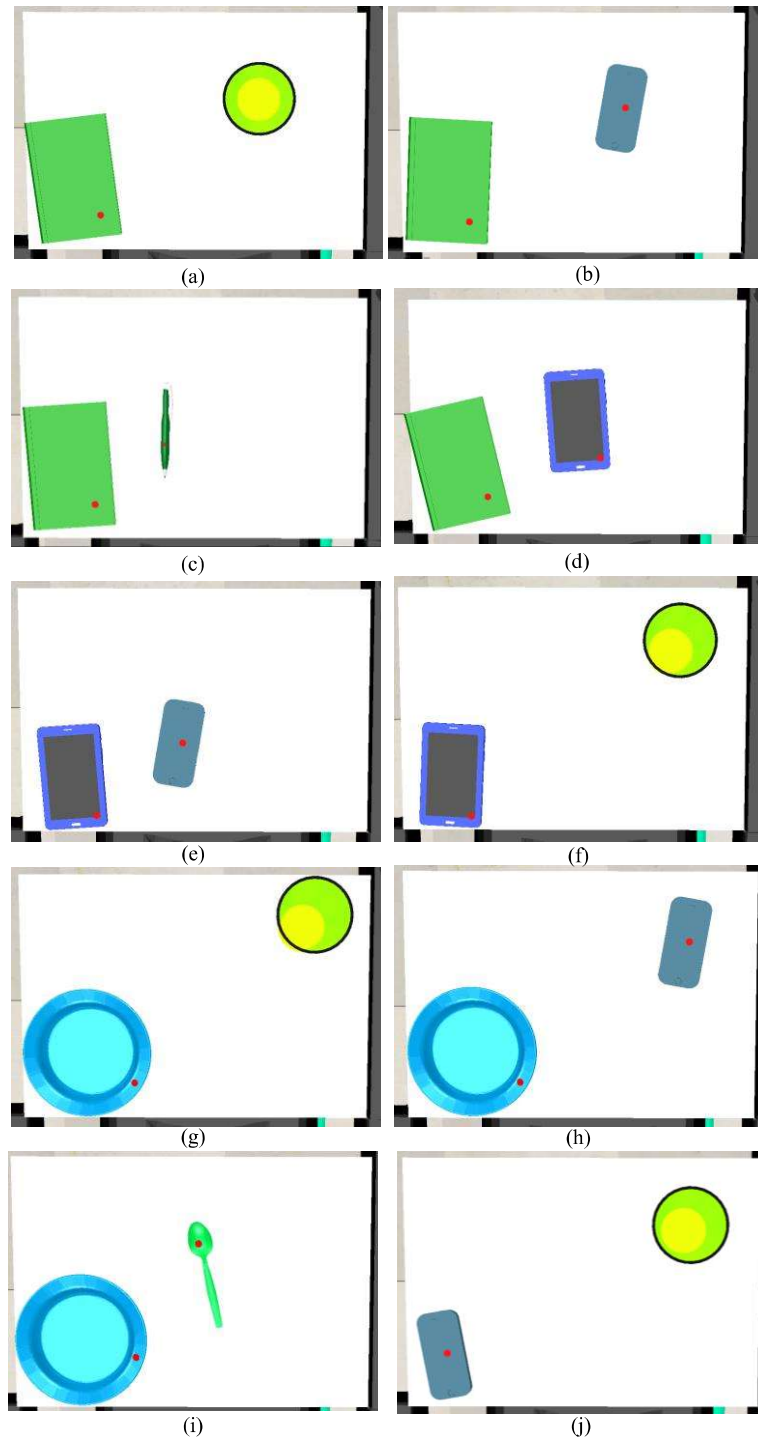


Figure 4.25: Object Placements in pairs in the simulation environment: (a). Book - Cup (b). Book - Phone (c). Book - Pen (d). Book - Tab (e). Tab - Phone (f). Tab - Cup (g). Plate - Cup (h). Plate - Phone (i). Plate - Spoon (j). Phone - Cup



Figure 4.26: Example for supported flat object

maximum error is recorded for the pair: plate and cup and it is equal to 2cm. It could be accepted considering the fact that the placing is not smooth as the real life scenario as the software lags and performance lags also accumulate towards this errors.

In all of the above mentioned experiments, a flat objects like book, phone and tab cannot be picked by the manipulator in the simulation if they lay flat on the table as the fingers cannot go under the object to grasp it. Hence, they are supported with a wedge to keep them vertical/close to vertical (see Fig. 4.26). In this way above mentioned obstacle will be averted and the manipulator can

easily grab that object. In real life applications, there are several types of such holders, commercially available.

## CONCLUSION AND FUTURE DIRECTIONS

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### 5.1 Conclusion

This thesis proposes, a controlling algorithm which can identify the user intentions for navigation and object manipulation of wheelchair with a robotic manipulator. Proposed system leverages the EMG of the user and the past experience of the user to understand the tasks on the wheelchair. Hence, the wheelchair is considered as an Intelligent wheelchair. Moreover, proposed navigation algorithm only requires the EMG of the user to generate the navigation commands. Hence, the need for sensor fusion is eliminated and the HITL controlling algorithm gives the user more flexibility in providing navigation commands to the wheelchair according to his/her intentions, than the existing wheelchair navigation algorithm. Moreover, it also reduces the misalignments in gripper pose during object grasping as the user can adjust the gripper pose according to his/her intentions using the EMG commands. Furthermore, user acceptance towards the proposed system could improve as object manipulation is done after performing a user study. In this way, system can adapt according to the user's past experience and preferences.

In the first stage of this research, available electric wheelchair was interfaced with PC. A healthy participant was able to control the wheelchair while giving the commands through a laptop while riding on it, successfully. Hence the dependence on the wheelchair joystick was eliminated. The only drawback that occurred was

that the wheelchair cannot achieve its different constant speed levels. Wheelchair works on its default constant speed.

In the next phase, EMG based controller was proposed to generate inputs that are required for directional commands in navigation of the IW and detection of user's intention for the use of the manipulator, through shifting states of sequence of four states. Moreover, it was tested with several healthy users of both genders to evaluate its controllability, adaptability and the versatility in performing the given tasks. Experiments revealed that the proposed controller can be adapted according to the user's EMG signal strength after performing few trials with the wheelchair users. Furthermore, it was discovered that with training, controller can be implemented on the wheelchair for real time applications. Even though the mean deviation of the for the threshold values were found to be  $\pm 0.03$ , 0.03, 0.09, 0.09 and 0.007 for right biceps brachii, left biceps brachii, left sternocleidomastoid, right sternocleidomastoid and triceps brachii of dominant arm respectively, those can be varied upon the types of the wheelchair users. The proposed controller can be considered as a reliable user intention based high level controller because the EMG signals can successfully detect the user intentions. Furthermore, it only uses EMG signals for the navigation input generation, shifting the states and input generation for robot manipulator and it has able to eliminate the requirement of merging another modality for the success of the controller.

The next stage of the research evaluates the user preferences in arranging the objects on a wheelchair tray. Studies reveal that the user preferences are affected by handedness of the user and the attributes of the objects. K means clustering algorithm was used to identify the clusters of the obtained data for the study. Revealed clusters emphasized that the wheelchair users tend to keep the objects with allying attributes close to each other whereas objects with the contrasting attributes are kept apart as far as possible. In this study usability of the objects at the same situation is highlighted as an allying attribute of the objects and potentially hazardousness of one object to the other is highlighted as

a contrasting attribute. The findings revealed by this study laid the platform to a compliant service to the wheelchair user which can be achieved through a user friendly object handling algorithm to handle the objects through a robot arm.

Finally the whole system was implemented inside the CoppeliaSim Simulation environment. Combination of both EMG based controller and the results obtained from the human study was incorporated to the simulation to the environment after adding improvements. Improved controller was tested with 4 healthy human subjects. Using the EMG of the healthy user, object manipulation tasks were performed for the three situations: dining, working and placing objects in pairs. Results revealed that the placing objects in dining and working situations are in accordance with the results obtained through human study for dining and the working situations. In the other scenario where the objects are placed in pairs maximum error reported was 2cm. It was reported for the object pair plate and the phone.

## 5.2 Future Directions

In the future the whole system is to be implemented on the powered electric wheelchair after adding required hardware modifications. In order to improve the versatility of the implemented controller, fusion of the sensors and different modalities can be added to the system.

The Restter of the proposed controller can be improved to eliminate the support of an external care giver when the Resetter is performed during an object manipulation task. Moreover, in this thesis wired EMG electrodes have been used. It could be improved to have wireless EMG electrodes so that the mobility of the wheelchair is not affected by the EMG electrode wires.

In this thesis, the system performance is tested with healthy human subjects. Clinical trials has to be performed in order to get the feedback from the actual

wheelchair users to improve the controller.



## LIST OF PUBLICATIONS

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### Articles Accepted/Submitted in Refereed International Conferences

#### Conference Papers

1. **R. A. M. Abayasiri**, A. G. B. P. Jayasekara, R. A. R. C. Gopura and Kazuo Kiguchi “Manipulation of EMG signals for tasks on the intelligent wheelchair”, 3rd International Conference on Electrical Engineering 2021

#### Journal Papers

1. **R. A. M. Abayasiri**, K. S. Priyanayana, M. M. S. N. Edirisinghe, A. G. B. P. Jayasekara, R. A. R. C. Gopura and Kazuo Kiguchi “A Human Study to Understand the Preferences of Wheelchair Users in Arranging Objects on Wheelchair Tray”, (Unpublished)

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## APPENDIX A

### CODES

---

#### A.1 Low level controller for wheelchair interface

This is the program that is used by the Micro-controller used in Fig. 3.1.

```
/* Defining Pins*/
#define fore_aft_out 3
#define lft_rgt_out 2
#define center_tap 4

/*PWM Values*/
int PWM_low = 80;
int center_val = 135;
int PWM_high = 175;

/*Control Commands*/
int command_out = 0;
char incommand=0;

void setup()
{
  pinMode(fore_aft_out, OUTPUT);
  pinMode(lft_rgt_out, OUTPUT);
```

```

pinMode(center_tap, OUTPUT);

/*Initializing Joysick*/
analogWrite(lft_rgt_out,center_val);
analogWrite(fore_aft_out,center_val);
analogWrite(center_tap,center_val);

Serial.begin(9600);
}

void loop()
{
if (Serial.available() > 0)
{
command_out = Serial.read();
//    command_out = (uint8_t)incommand;
if (command_out == 'W' || command_out == 'w')
{
analogWrite(lft_rgt_out,center_val);
analogWrite(fore_aft_out,PWM_high);
Serial.print("Forward \n");
}
else if (command_out == 'S' || command_out == 's')
{
analogWrite(lft_rgt_out,center_val);
analogWrite(fore_aft_out,PWM_low);
Serial.print("Backward \n");
}
else if (command_out == 'M' || command_out == 'm')
{

```

```

analogWrite(lft_rgt_out,center_val);
analogWrite(fore_aft_out,center_val);
Serial.print("Center \n");
}
else if (command_out == 'A' || command_out == 'a')
{
analogWrite(lft_rgt_out,PWM_low);
analogWrite(fore_aft_out,center_val);
Serial.print("Left \n");
}

else if (command_out == 'D' || command_out == 'd')
{
analogWrite(lft_rgt_out,PWM_high);
analogWrite(fore_aft_out,center_val);
Serial.print("Right \n");
}
}
}
}

```

## A.2 MATLAB scripts required for the proposed system

MATLAB scripts reacquired for the critical steps are mentioned here. Some codes are omitted as they are exactly similar in the algorithms mentioned in this section (only the variables change).

### A.2.1 MATLAB Script for Navigation

This script is called in the main code as “Nav-code”.

```

if left > .3
left_turn
fprintf(ardSP,'%c','A');
disp('Left');

elseif right > .18
right_turn
fprintf(ardSP,'%c','D');
disp('Right');

elseif foward > .2
forward_run
fprintf(ardSP,'%c','W');
disp('Foward');

elseif backward > .2
backward_run
fprintf(ardSP,'%c','S');
disp('Backward');

else
fprintf(ardSP,'%c','M');
disp('Center');

end

```

## **MATLAB Script for Forward Navigation**

This script is called in the Navigation code as “forward-run”.

```
disp('Forward');
```

```

[rob]= sim.simxAddStatusbarMessage(clientID,'Forward',sim.simx_opmode_oneshot);

r = 0.125;      %Radius of the wheel
d = 0.42;      %Distance between two wheels
V_rob = 0.1;    %Forward Velocity
Rot_rob = 0;    %Rotation (turn) of the robot

%%%%%%%% Calculating Linear Velocities of Large wheels
VRW = V_rob + d * Rot_rob/2;
VLW = V_rob - d * Rot_rob/2;

%%%%%%%% Calculating Rotational Velocities of Large wheels
Rot_RW = VRW/r;
Rot_LW = VLW/r;

sim.simxSetJointTargetVelocity (clientID,JLW,Rot_RW,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRW,-Rot_LW,sim.simx_opmode_blocking);

sim.simxSetJointTargetVelocity (clientID,JLFH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRFH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRRH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLRH,0,sim.simx_opmode_blocking);

sim.simxSetJointTargetVelocity (clientID,JRFW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRRW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLFW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLRW,0,sim.simx_opmode_blocking);

```

## MATLAB script for Backward Navigation

This script is called in the Navigation code as “backward-run”.

```
disp('Backward');
[rob]= sim.simxAddStatusbarMessage(clientID,'Backward',sim.simx_opmode_oneshot);

r = 0.125;      %Radius of the wheel
d = 0.42;      %Distance between two wheels
V_rob = -0.1;   %Forward Velocity
Rot_rob = 0;    %Rotation (turn) of the robot

%%%%%%%% Calculating Linear Velocities of Large wheels
VRW = V_rob + d * Rot_rob/2;
VLW = V_rob - d * Rot_rob/2;

%%%%%%%% Calculating Rotational Velocities of Large wheels
Rot_RW = VRW/r;
Rot_LW = VLW/r;

sim.simxSetJointTargetVelocity (clientID,JLW,Rot_RW,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRW,-Rot_LW,sim.simx_opmode_blocking);

sim.simxSetJointTargetVelocity (clientID,JLFH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRFH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRRH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLRH,0,sim.simx_opmode_blocking);

sim.simxSetJointTargetVelocity (clientID,JRFW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRRW,0,sim.simx_opmode_blocking);
```



```
sim.simxSetJointTargetVelocity (clientID,JLFW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLRW,0,sim.simx_opmode_blocking);
```

## MATLAB script for Left Turn

This script is called in the Navigation code as “left-turn”.

```
disp('Left');
[rob]= sim.simxAddStatusbarMessage(clientID,'Left',sim.simx_opmode_oneshot);

r = 0.125;      %Radius of the wheel
d = 0.42;      %Distance between two wheels
V_rob = 0.1;    %Forward Velocity
Rot_rob = -.2;  %Rotation (turn) of the robot

%%%%%%%%% Calculating Linear Velocities of Large wheels
VRW = V_rob + d * Rot_rob/2;
VLW = V_rob - d * Rot_rob/2;

%%%%%%%%% Calculating Rotational Velocities of Large wheels
Rot_RW = VRW/r;
Rot_LW = VLW/r;

sim.simxSetJointTargetVelocity (clientID,JLW,Rot_RW,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRW,-Rot_LW,sim.simx_opmode_blocking);

sim.simxSetJointTargetVelocity (clientID,JLFH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRFH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRRH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLRH,0,sim.simx_opmode_blocking);
```

```

sim.simxSetJointTargetVelocity (clientID,JRFW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRRW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLFW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLRW,0,sim.simx_opmode_blocking);

```

## MATLAB script for Right Turn

This script is called in the Navigation code as “right-turn”.

```

disp('Right');
[rob]= sim.simxAddStatusbarMessage(clientID,'Right',sim.simx_opmode_oneshot);

r = 0.125;      %Radius of the wheel
d = 0.42;      %Distance between two wheels
V_rob = 0.1;    %Forward Velocity
Rot_rob = .2;   %Rotation (turn) of the robot

%%%%%% Calculating Linear Velocities of Large wheels
VRW = V_rob + d * Rot_rob/2;
VLW = V_rob - d * Rot_rob/2;

%%%%%% Calculating Rotational Velocities of Large wheels
Rot_RW = VRW/r;
Rot_LW = VLW/r;

sim.simxSetJointTargetVelocity (clientID,JLW,Rot_RW,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRW,-Rot_LW,sim.simx_opmode_blocking);

sim.simxSetJointTargetVelocity (clientID,JLFH,0,sim.simx_opmode_blocking);

```

```

sim.simxSetJointTargetVelocity (clientID,JRFH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRRH,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLRH,0,sim.simx_opmode_blocking);

sim.simxSetJointTargetVelocity (clientID,JRFW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JRRW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLFW,0,sim.simx_opmode_blocking);
sim.simxSetJointTargetVelocity (clientID,JLRW,0,sim.simx_opmode_blocking);

```

## A.2.2 MATLAB script for Object searching

```

d1 = 20.50;
d2 = 7.05;
a3 = 41.0;
a5 = 13.71;
d5 = 27.15;
d6 = 16.41;
d7 = 10.0;
qz=([0,0,0,0,0,-pi/2]); % Pose for the start of the object search

```

%Defining the DH Parameters

```

L(1) = Revolute('d', d1, 'a', 0, 'alpha', 0 );
L(2) = Revolute('d', d2, 'a', 0, 'alpha', pi/2);
L(3) = Revolute('d', 0, 'a', a3, 'alpha', 0);
L(4) = Revolute('d', 0, 'a', 0, 'alpha', pi/2);
L(5) = Revolute('d', d5, 'a', a5, 'alpha', 0);
L(6) = Revolute('d', d6, 'a', 0, 'alpha', -pi/2);
% L(7) = Revolute('d', d7, 'a', 0, 'alpha', 0);

```

```

arm = SerialLink(L, 'name', 'Jaco 2');
% arm.teach
arm.plot(qz)

pose_init = arm.fkine(qz);      %Initial Pose for the searching
pose_final = pose_init;
pose_final(1,4) = pose_init(1,4)+25; %Final Pose

search_traj = cttraj(pose_init,pose_final,20); %Calculating the Trajectory

joint_var = arm.ikine(search_traj); %Calculating the joint variables

if blob_var == false
for i=1:20

arm.fkine(joint_var(i,:))

end

end

```

### A.2.3 MATLAB script for Blob Detection

```

a = imaqhwinfo;
[camera_name, camera_id, format] = getCameraInfo(a);

% Capture the video frames using the videoinput function
% You have to replace the resolution & your installed adaptor name.
vid = videoinput(camera_name, camera_id, format);

```

```

% Set the properties of the video object
set(vid, 'FramesPerTrigger', Inf);
set(vid, 'ReturnedColorspace', 'rgb')
vid.FrameGrabInterval = 5;

%start the video aquisition here
start(vid)

% Set a loop that stop after 100 frames of aquisition
while(vid.FramesAcquired<=20)

% Get the snapshot of the current frame
data = getsnapshot(vid);

% Now to track red objects in real time
% we have to subtract the red component
% from the grayscale image to extract the red components in the image.
diff_im = imsubtract(data(:,:,1), rgb2gray(data));
%Use a median filter to filter out noise
diff_im = medfilt2(diff_im, [3 3]);
% Convert the resulting grayscale image into a binary image.
diff_im = im2bw(diff_im,0.1);

% Remove all those pixels less than 300px
diff_im = bwareaopen(diff_im,50);

% Label all the connected components in the image.
bw = bwlabel(diff_im, 8);

% Here we do the image blob analysis.

```

```

% We get a set of properties for each labeled region.
stats = regionprops(bw, 'BoundingBox', 'Centroid');

% Display the image
imshow(data)

hold on
%This is a loop to bound the red objects in a rectangular box.
for object = 1:length(stats)
    bb = stats(object).BoundingBox;
    bc = stats(object).Centroid;
    rectangle('Position',bb,'EdgeColor','r','LineWidth',2)
    plot(bc(1),bc(2), '-m+')
end

hold off

end

% Both the loops end here.

% Stop the video aquisition.
stop(vid);
% Flush all the image data stored in the memory buffer.
flushdata(vid);
blob_var = true;

```

#### A.2.4 MATLAB script for Object Reaching

```

%Reaching towards object
if blob_var == true

```

```

T_reach_init = arm.fkine(joint_var(i,:));
T_reach_final = T_reach_init;
T_reach_final(1,4) = T_reach_init(1,4)+20;

reach_traj = ctraj(T_reach_init,T_reach_final,20);%Calculating Trajectory
joint_var_reach = arm.ikine(reach_traj); %Calculating the joint variables

if sonar_val == 30      %Checking whether sonar reached towrds the object
reach_start = true;

else
reach_start = false;
end

if reach_start == false
for j=1:20

arm.fkine(joint_var_reach(j,:));

end
end
end

```