Design and Control of Upper Arm Exoskeleton for Arm Movement Assistance

A thesis submitted in partial fulfillment of the requirements for the award of the degree of

B.Tech

in

Instrumentation and Control Engineering

By

Arunagiri R (Roll No. 110116009)

Bharath Kumar R (Roll No. 110116019)

Keerthana J (Roll No. 110116041)

INSTRUMENTATION AND CONTROL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
TIRUCHIRAPPALLI – 620015

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BONAFIDE CERTIFICATE

This is to certify that the research project titled **Design and Control of Upper Arm Exoskeleton for Arm Movement Assistance** is a bonafide record of the work done by

Arunagiri R (Roll No. 110116009)

Bharath Kumar R (Roll No. 110116019)

Keerthana J (Roll No. 110116041)

in partial fulfillment of the requirements for the award of the degree of **Bachelor of Technology** in **Instrumentation and Control Engineering** of the **NATIONAL INSTITUTE OF TECHNOLOGY, TIRUCHIRAPPALLI**, during the year 2020.

Dr. R Periyasamy	**Dr. G Uma**
Guide	Head of the Department

Project Viva-voce held on ________________________

Internal Examiner	**External Examiner**

ABSTRACT

This research presents a controller implementation of an two degree of freedom upper arm exoskeleton. Upper arm exoskeletons have potential applications in the field of medical rehabilitation. A patient with limb paralysis and history of stroke will be trained with upper arm exoskeleton for arm motion assistance during rehabilitation. In such conditions, An upper arm exoskeleton is prone to coming in contact with its environment. The contact with objects in the environment introduces a coupled dynamics involving both the exoskeleton and the object. This seemingly insignificant change can sometimes be fatal to the wearer when the combined dynamics results in destabilization of the exoskeleton system. To counter this problem, an impedance controller is implemented for the trajectory tracking of the exoskeleton. The impedance controller introduces compliance between the exoskeleton and the object, striking a perfect balance by not giving away the safety of the wearer while accurately tracking the reference trajectory of the end-effector. A gravity compensation term is further added on top of impedance control to remove the effects of gravitation terms in the system dynamic model of the upper arm exoskeleton.

Keywords : Compliance; Impedance Control; Gravity Compensation; Rehabilitation

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Pragmatic decision due to COVID-19 pandemic

Our initial plan for the project titled ”Design and Control for Upper Arm exoskeleton for Arm Movement Assistance” is to construct a solid model of the upper arm exokeleton, design a controller, conduct simulations and practically implement the controller in the 3D print of the the solid model design of upper arm exoskeleton. However, due to unforeseen circumstances and lockdown measures, we had to modify our project timeline. We couldn’t work past simulation, as we required 3D print of our exoskeleton design. So we have proceeded with a new timeline involving mathematical modelling, solid modelling, designing a controller and performing simulations, and worked out best to obtain fruitful results for our project.

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CHAPTER 1
INTRODUCTION

1.1 Introduction to Exoskeletons

Robotic exoskeletons or powered exoskeletons are considered wearable robotic units controlled by computer boards to power a system of motors, pneumatics, levers, or hydraulics to restore locomotion. Unlike serial robotic manipulators which interact with human operators at the end-effector, exoskeletons cover the human limb in one or more joints, and synchronously moves with the human's joints. This design, on the one hand, enables more application potentials, like strength augmentation, movement correction akin to an orthosis, or natural teleoperation, yet on the other hand, brings challenges in mechanism design, actuation and power transmission, manufacturing, sensing, and control algorithms development, which require a deep understanding of human anatomy, motor control, biomechanics, etc.

The topic of exoskeletons is timely given the number of devices currently being studied as well as purchased by facilities for rehabilitation purposes in medical centers or for home use. Exoskeletons have emerged as an advantageous rehabilitation tool for disabled individuals with spinal cord injury (SCI), lower paralysis and individuals with a history of stroke. Rehabilitation specialists, clinicians, researchers, and patients welcome their use for over ground ambulation. Compared to previously existing loco motor training paradigms, exoskeletons may offer a great deal of independence in medical centers and communities including shopping malls, local parks and movie theaters as well as improving the level of physical activity. There is a pressing need for this population to improve their levels of physical activity. This feature may encourage continuous usage of exoskeletons in conjunction with wheelchairs.

There are a huge number of different exoskeletons. The most common categorization of exoskeleton are:

1. Upper Extremity Exoskeletons

2. Lower Extremity Exoskeletons

1.1.1 Upper Extremity Exoskeletons

The first powered upper limb exoskeleton is generally considered to be the Hardiman, developed in the 1960s by General Electric and the US armed forces. Initial designs were frequently targeted at augmenting capabilities for soldiers, and this remains an active area of research (e.g., the SARCOS series). Later, in order to alleviate the lack of experienced physical therapists, the applications extended to rehabilitation, which requires better human-in-the-loop understanding, like intention detection and motion control. These systems branched out to become much of rehabilitative robotics. Additionally, as the world population has aged, increased focus has shifted toward exoskeletons designed for assisting the elderly or disabled without expectation of recovery, such as those MyoPro systems developed based on the Myomo e100 NeuroRobotic System. Due to the cost of human labor in labor-intensive industries such as construction and manufacturing, and employer desire to reduce injuries due to moving heavy objects, numerous exoskeletons began to be developed to augment wearers in industry.

Lastly, numerous upper limb exoskeletons have been developed for other purposes such as teleoperation and as haptic devices in virtual reality (VR) environments. For all these systems, the historical trend has been for the need for active systems due to the inadequacy of purely passive ones. In the last two decades, the upper-limb exoskeletons used for services and rehabilitation have attracted a lot of attention from the biomedical and engineering sectors. The technology is becoming important as a potential solution for physically weak or disabled people. Systems have been developed to improve the performance and strength of the wearer. Giving high utility and growing demand for upper-limb exoskeletons, the technology is still challenging in the area of mechanism designs, controls, and human–robot interaction.

Mechanical design and kinematic analysis are the most crucial issues in developing an ergonomic exoskeleton system. A number of research articles have reviewed upper-limb exoskeletons, particularly for services and medical applications. In addition, performance and effect of these systems are issues being studied extensively. The development in hardware systems of active upper-limb exoskeleton robots was presented in Reference by considering the pHRI. A study on the development of upper-limb hybrid exoskeletons in combination with the functional electrical stimulation (FES) was reported by Stewart, which mainly focused on post-stroke rehabilitation and patient monitoring.

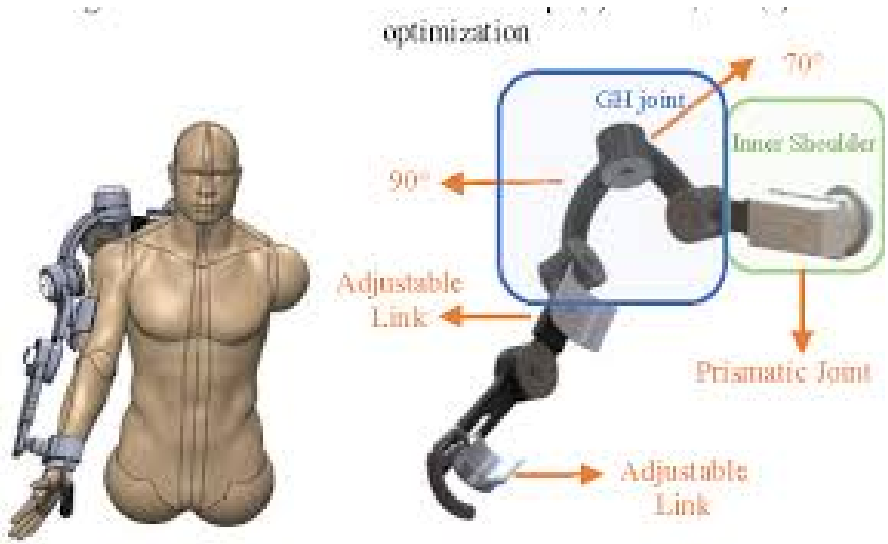

Figure 1.1: Exoskeleton for Upper Limb Extremity et al. [13]

Islam made a review to identify the technological gap between the commercially available robotic exoskeletons and research prototypes used for post-stroke rehabilitation. However, given the extensive studies on the upper-limb exoskeletons, very few articles have reported the exoskeleton's design addressing complex anatomical movements at the shoulder and wrist joints of the arm and hand as a whole. It is well understood that exoskeleton robots are highly nonlinear mechatronic systems, and different engineering methods have been used to improve the physical human–robot interaction (pHRI). The interaction between human and the robotic exoskeletons is affected fundamentally by the following: Mechanisms are designed by considering sophisticated biological features and activities for improved pHRI; Mode of actuation and transmission need to be selected in a systematic way by taking in account the compliance/stiffness factor; The selection of the control method also influences the pHRI.

1.1.2 Lower Extremity Exoskeletons

Lower extremity exoskeletons developed for human locomotion assistance are primarily used to help paralyzed patients who have completely lost mobility in the lower limbs. Exoskeletons can provide external torque at the positions of human joints to replace the patients' deficient motor function, and thereby give these patients greater strength to regain the ability to perform essential daily life motions such as standing up, sitting down, and walking. The ReWalk exoskeleton developed by ReWalk Robotics (Marlborough, MA, USA) is a LEEs that provides powered hip and knee motion to enable individuals with SCI to stand upright and walk . It is the first exoskeleton suit cleared by the U.S. Food and Drug Administration in 2014 to be used as a personal device at home and in the community. The exoskeleton is controlled by on-board computers with motion sensors, restores self-initiated walking by sensing the forward tilt of the upper body, and mimics the natural gait pattern of an able-bodied person.

Based on clinical study results of the ReWalk exoskeleton , paralyzed patients can practically stand upright and walk with increased independence and their quality of life is greatly improved. These results also indicate that the patients experienced a reduction in secondary complications resulting from life in a wheelchair such as depression and neuropathic pain. The Vanderbilt exoskeleton developed by Goldfarb is another LEE that enables paralyzed patients to perform basic motions such as walking, sitting, standing, and walking up and down stairs.

Figure 1.2: Exoskeleton for Lower Limb Extremity et al. [14]

It adopts a modular-based design that paralyzed patients themselves can quickly assemble and put on or disassemble. Each thigh segment is designed with two brushless direct current (DC) motors, which are used to actuate the hip and knee joints. Its total weight is only 12 kg, which is relatively light, compared to other similar exoskeletons. This exoskeleton has been implemented in a patient with a T10 motor and sensory complete injury and the exoskeleton can provide a repeatable gait with knee and hip joint amplitudes that are similar to those observed during nonSCI walking. With the help of the exoskeleton, the patient is able to stand up and sit down, walk, turn, and go up and down stairs.

The LEEs developed at the Chinese University of Hong Kong (CUHK-EXO) in Hong Kong, China also targets locomotion assistance of paralyzed patients. The exoskeleton has six DOFs in total, among which hip and knee flexion/extension are actuated by DC motors and ankle joints are passive. A pair of smart crutches equipped with force and attitude sensors were designed for the exoskeleton system for comfortable and stable assistance. Smartphone application was also developed to make the exoskeleton system easier for patients and therapists to learn and use. The developers have recruited four paralyzed patients for relevant clinical trials.

1.2 Exoskeleton Control Strategies

To command the upper limb exoskeleton to accomplish a task together with a human in the loop, the system needs to transmit the sensed signals via a controller to actuators. Upper limb exoskeleton systems are categorized into different control strategies, which sometimes may in reverse tell what functionalities the system has. Based on the difference in applications, researchers utilized control strategies including but not limited to the following.

1.2.1 Position/velocity control:

Often used in passive motion like predefined trajectory following or teleoperation, position/velocity control aims to achieve a desired joint position/velocity in order to track a trajectory.

1.2.2 Force/torque control

To provide assistance or even further augment the user's capability, a controller may estimate how much force/torque is needed and send the command to the actuators. Force/torque control is also often combined with biosignal control discussed below.

1.2.3 Admittance control:

The admittance controller accepts effort (e.g., force/torque signals) as inputs and yield flow (e.g., desired position commands) to actuators. If force/torque sensors are equipped on the humanmachine interface, the user's movement would produce an interaction force which directly results in exoskeleton movement. Tuning the "stiffness" makes the user feel that the exoskeleton is difficult or easy to move. The user always feels some "resistance," which sacrifices as input to the controller—overtuning the sensitivity may make the system unstable and oscillate with tiny unwanted movements.

1.2.4 Master/slave system:

Exoskeleton users could build interconnections using teleoperation: one wears an exoskeleton as the master side and teleoperates the slave side—another exoskeleton worn by another user. The communication could be unilateral or bilateral, and position control or force control could be used based on the functionality needed. This framework could also be expanded to scenarios with different types of slave side: to teleoperate an industrial manipulator in hazardous materials handling, underwater or extraterrestrial exploration; to teleoperate an avatar in VR in poststroke rehabilitation training; the healthy side teleoperates the affected side in poststroke upper extremity rehabilitation training (bimanual mode)

1.2.5 Biosignal control

This control approach does not rely on force or position information measured from the humanmachine interface, but more on biosignals like sEMG and EEG which could directly tell which joints should move. Mapping from the measured signals to control signals, however, needs to be determined based on the system's complexity (e.g., number of DoFs) in kinematics and dynamics. One may also find hybrid control strategies with other names like AAN (assist-as-needed) control, adaptive control, etc.

1.3 Impedance Control

Impedance control is a unique control scheme that is employed to achieve desirable dynamic interaction between a manipulator and its environment. The impedance usually refers to the dynamic relationship between the motion variables of manipulators and the contact forces. For robotic manipulation, the target of impedance control is to control this dynamic relationship to fulfill the requirements of a specified interaction task, such as keeping the contact force always in a preset safe or acceptable range when the robotic equipment is tracking the desired motion trajectory.

Compared with other regular robotic control schemes, such as position control, force control, and hybrid position/force control, impedance control has three distinguished features. First, the core idea of impedance control is to control the dynamic interaction between motion and contact force as desired instead of controlling these variables separately. Second, impedance control can be utilized in all manipulation phases consisting of free motion, constrained motion, and the transient process between them, without the need to switch different control modes. Last, impedance control provides a possibility to control motions and contact forces simultaneously by designing a proper interaction between a manipulator and its environment. As a result, the performance of robotic manipulation can be improved, and the safety of human–robot interaction can be guaranteed. With impedance control, the application domain of robotic manipulation can be significantly broadened.

Human beings have been dreaming that artificial objects can perform like themselves. Impedance control, originated from the observation and investigation of human motor mechanism, has the potential to offer robotic manipulators with human-like elaborated operating ability. To understand human motor mechanisms, the function of muscles should be addressed. Hogan stated that it is not adequate to simply regard muscle as a generator of forces, but a mechanical impedance adjuster of human limbs. The role of a force generator is to actuate the motion of limbs, whereas the function of an impedance adjuster is to determine the interaction between the limbs and the environment.

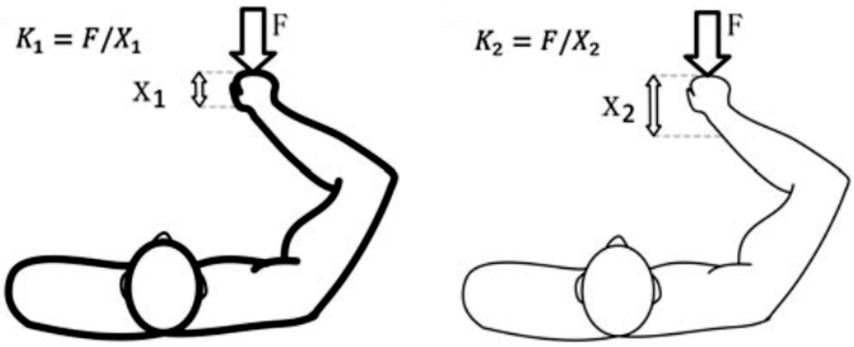

Figure 1.3: The Impedance of Human Arm (K is the stiffness factor) et al. [15]

Human locomotion is another good example to depict how humans interact with the environment through impedance. When humans are walking, the leg muscles are repeatedly hardened and relaxed depending on the gait phase. Just before the contact of the swing foot with the ground, the leg muscles are relaxed to reduce the leg impedance, which results in a soft landing on the ground. Inspired by the human motor mechanism, the concepts of impedance and impedance control were applied to robotic manipulation. The impedance actually defines the dynamic response of the manipulator to its environment. This dynamic relationship can be well designed to realize compliant motion or delicate interaction. Commonly, to implement impedance control, the coupled stability of a manipulator and its environment should be considered first. Then a proper implementation method should be determined according to the hardware conditions and the actual operating requirements.

In general, all these implementation methods can be classified into two main categories: hardware-based approach and software-based approach. In the hardware-based approach, the inherent compliance of some hardware elements, such as stiffness-variable springs and variable dampers, is utilized to achieve the effect of impedance control. By contrast, the software-based approach adopts the well-designed control laws at the software level to impose the desired impedance on the hardware. After the basic theories and implementations of impedance control have been established, most research efforts were devoted to two main fields: developing more advanced impedance control techniques and expanding the application range of impedance control. Regarding the control techniques, the impedance control is combined with all sorts of advanced control algorithms to achieve the enhanced performance. For example, to promote the force-tracking ability of impedance control, the modified impedance model and different algorithms were adopted; to increase the flexibility of manipulation, hybrid impedance control was proposed; to strengthen the robustness and adaptability toward the model uncertainties of manipulators or unknown environments, various robust and adaptive control algorithms were integrated into the fundamental impedance control methods.

In addition, the different learning impedance controllers with the self-adjusting ability in unknown environments were developed by utilizing the diverse learning algorithms. In the field of applications so far, human–machine interaction and mechanical manipulation are two main directions to apply impedance control. The applications toward human machine interaction include rehabilitation robots, collaborative robots, and some expert teaching systems. The applications toward mechanical manipulation involve industrial robots, micro-manipulation systems, and other specific manipulation applications. Utilizing impedance control to achieve compliant motion or elaborate interaction force is the motivation of all these applications.

1.4 Applications of Upper Arm Exoskeleton

Upper arm exoskeleton includes a wide area of medical, civil and military applications. Some of the applications are Power amplification in industrial environment, neuromuscular impairment compensation, post-stroke rehabilitation and support for disabled people in their activities of daily living. In past few years, exoskeletons are widely used for rehabilitation. It has had a lot of attention in engineering and biomedical sectors. This system can be used to improve the performance and strength of the user. Giving high utility and growing demand for upper-limb exoskeletons, the technology is still challenging in the area of mechanism designs, controls, and human–robot interaction. Mechanical design and kinematic analysis are the most crucial issues in developing an ergonomic exoskeleton system. A number of research articles have reviewed upper-limb exoskeletons, particularly for services and medical applications. In military, this system can help the soldiers to transport heavy weapons and machines with less human power. The upper exoskeleton contains actuators which can amplify the strength based on their specifications. This can also be used in industries for the same to reduce human effort. This exoskeleton can also be used for rehabilitation of physically impaired patients suffering from post-stroke paralysis, amyotrophic lateral sclerosis, or other physical or cognitive impairments. Additionally, these devices can be employed to provide therapy consistently for a longer period, irrespective of the fatigue level and training skill of physiotherapists.

CHAPTER 2
LITERATURE REVIEW

This section provides an overview for upper limb exoskeleton systems. These systems can be broadly categorized into assistive devices meant to replace impaired human functioning, rehabilitation devices aimed at recovering functionality lost due to injury or medical conditions, augmentation exoskeletons designed to enhance the users' abilities above their normal levels.

Exoskeleton are highly nonlinear mechatronic systems, and different engineering methods have been used to improve the physical human–robot interaction (pHRI).The interaction between human and the robotic exoskeletons is affected fundamen-tally by the following: 1. Mechanisms are designed by considering sophisticated biological features and activities for improved pHRI. 2. Mode of actuation and transmission need to be selected in a systematic way by taking in account the compliance/stiffness factor. 3. The selection of the control method also influences the pHRI.

Gull, Muhammad A.; Bai, Shaoping; Bak, Thomas. 2020. "A Review onDesign of Upper Limb Exoskeletons." Robotics 9, no. 1: 16

2.1 Design Requirements for the exoskeleton

The following requirements were formulated for a rehabilitation hand exoskeleton that attaches to an arm exoskeleton:
1. Low Mass: Mass at the hand must be minimized to reduce required torque of the upper limb exoskeleton.
2. Torque: The torque capabilities of the exoskeleton must be sufficiently large to actuate the hand.
3. Workspace: The workspace of the exoskeleton must contain the workspace of the human hand.
4. Grasp: It must be able to actuate a variety of grasps.
5. Open Palm: It must leave the palm and fingers unoccupied to permit interaction with physical objects.

6. Unisize: It must fit 95% of the general population.

ABS is chosen as the choice of material because of the following properties:

General Properties ABS				
Density	1,01E+03	-	1,21E+03	kg/m^3
Price	20,6	-	24,3	SEK/kg

Mechanical Properties ABS				
Young´s Modulus	1,1	-	2,9	GPa
Yield strength (elastic limit)	18,5	-	51	MPa
Tensile strength	27,6	-	55,2	MPa
Compressive strength	31	-	86,2	MPa
Elongation	1,5	-	100	% strain
Hardness (Vickers)	5,6	-	15,3	HV

Thermal Properties ABS				
Glass temperature	87	-	128	°C
Maximum service temperature	61	-	76	°C
Minimum service temperature	-123	-	-73	°C

Optical Properties ABS	
Transparency	Opaque

Process Ability ABS			
Castability	1	-	2
Moldability	4	-	5
Machinability	3	-	4
Weldability	5	-	

Scale: 1→Excellent; 5→Not recommended

Figure 2.1: Properties of ABS

Component	Specifications
Arm Straps	Nylon
Support Material	ABS/Steel
Servo Motors	Torque = rF = lmg Where 'l' is the length of the arm and 'm' is the mass to be lifted
Servo Encoders	As per the servo compatibility
Screw, Nuts and Bolts	As per the requirement
Power Tools	As per the requirement

Figure 2.2: Components and the materials

This robot arm is designed to have low inertia, high stiffness link, and zero backlash transmissions. It supports the patient's arm during rehabilitation which is a repetitive task and takes a period of time.

Exoskeleton arm for Therapeutic Applications and Augmented Strength by Dinumol Varghese1, Rahim T.S1, Leya Achu Bijoy1, Bibin K Abraham1, Dinto Mathew2(June 2019)

2.2 Kinematics of the Exoskeleton

The kinematics and dynamics of the human arm during activities of daily living are studied in part to determine the engineering specifications for the exoskeleton design. The model for the exoskeleton include forward kinematic, inverse kinematic, and dynamic model. The kinematics are used to calculate the relation between the joint angles and the arm position, while the dynamic model is applied to design controllers.

The upper limb is composed of segments linked by articulations with multiple degrees of freedom.Three ridged segments, consisting of the upper arm,lower arm and hand connected by friction-less joints make up the simplified model of the human arm. Placing a reference frame at the shoulder, the upper arm and torso are rigidly attached by a ball and socket joint.The connection between the upper and lower arm segments can be regarded as a single rotational joint at the elbow. These motions can be regarded as several joint rotations as in Fig 2.3.

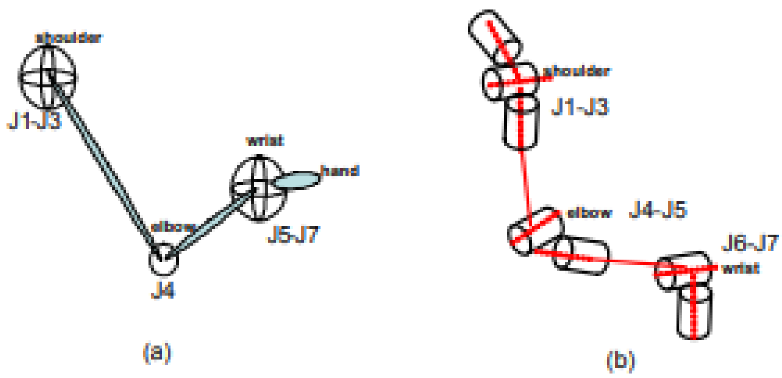

Figure 2.3: Human arm rotation

Javier Garrido, Wen Yu, Alberto Soria "Modular Design and Modeling of an Upper Limb Exoskeleton(Aug. 2014)"

2.3 Control Strategies

Control strategies of exoskeletons involving physical interaction with patient's limbs have to be implemented carefully keeping in mind the safety. In recent years people have tried to extract information from patient's bio signals which can effectively reflect patient's movement intention and muscle activation. Hence few control strategies which integrate the hybrid data fusion(postion,force and bio-signals) and adaptive tuning law are analysed. The following control strategies are analysed on their respective characteristics and outcomes: Position control,Force and Impedance control,EMG-based control and Adaptive control.

Control strategies	Methods	Characteristics	Representative studies	Outcomes
Position control	Trajectory tracking control	It is the basis for other strategies; repeated passive training can be achieved by this strategy; the trajectory generation and high control accuracy are key issues.	Emken et al. [54], Vallery et al. [55], Duschau-Wicke et al [56], Saglia et al. [31], Jamwal et al. [48], Hussain et al. [50], Beyl et al. [57]	Essential in early rehabilitation, help to achieve continuous and repetitive training but in a passive way, lacking initiatives
Force and impedance control	Hybrid position/force control	It can be applied for strengthening exercises; selection matrix can be used to divide the control into an independent position control loop and a force control loop.	Ju et al. [58], Simon et al. [59], Deutsch et al. [60], Bernhardt et al. [61], Banala et al. [62], Duschau-Wicke et al [56]	Robot moves along the desired trajectory and maintains certain interaction force, thus can help strengthen patient's muscles
	Impedance control	It is one of the most appropriate approaches for rehabilitation; can regulate the dynamic relationship between robot position and contact force; more and more devices are using impedance control algorithms.	Duschau-Wicke et al. [56], Veneman et al. [18], Hussain et al. [51], Roy et al. [63], Emken et al. [64], Koopman et al. [65], Agrawal et al. [66]	Human-robot interaction will be enhanced, the impedance can be adjusted to make the robot compliant, flexible, adaptable to patient's recovery needs
EMG-based control	EMG-triggered control	It is a muscular activation controlled method; predict patient's motion intention in advance and the robot assistance will be triggered when it reaches a certain threshold.	Krebs et al. [67], Kiguchi et al. [68], Kawamoto et al. [69], Fleischer et al. [70], Yin et al. [71]	It encourages self-initiated movement by patients, but there is no interaction during the robot movement until the next EMG trigger occurs
	EMG-based continuous control	It utilizes EMG signals to decode the human motion, e.g. estimate the joint angle or torque; control robot in a continuous way, or provide continuous torque assistance proportional to EMG signals.	Song et al. [72] [73], Komada et al. [53], Lenzi et al. [74], Sawicki and Ferris [25, 75], Fan et al. [76]	Patient can keep controlling the robot during exercise, instead of just triggering the robot once, can provide a continuous interaction to the patient
Adaptive control	Movement ability-based adaptive control	It can make the robot's behaviour more flexible and adjustable to the patient's ability and participation; set the robot assistance level to patient's movement ability in terms of active force or tracking errors.	Emken et al. [54], Hussain et al. [51], Riener et al. [77], Wolbrecht et al. [78], Blaya and Herr [24]	Patient can take the maximum efforts instead of relying on robot, by adjusting the robot impedance and assistance level when patient shows a better movement ability
	EMG-based evaluation and adaptive control	It enables the robot be controlled in a more natural way using muscles; it builds the relationship between EMG signals and muscle activity and adjusts the robot assistance level to patient's muscle recovery needs.	Colombo et al. [79], Krebs et al. [67], Kiguchi et al. [80, 81], Zhang et al. [82], Kwakkel et al. [9]	Robot assistance force and impedance can be adaptable to patient's muscle activity level, enhance the robot's adaptive adaptability and improve the human-machine interaction
	Assist-as-needed control	It is one of the most prevailing paradigms to encourage patients' active participation; also refers to as cooperative, adaptive, interactive control; It considers the patient's intention rather than imposing an inflexible control strategy; it can do the exercise like a physiotherapist.	Marchal-Crespo and Reinkensmeyer [7], Riener et al. [77] [83], Duschau-Wicke et al [56], Banala et al. [62], Fleerkotte et al. [39], Hogan and Krebs [84], Wolbrecht et al. [78]	AAN methods can be adaptive to patients' needs and assist the movement only as much as needed, encouraging them to take maximal voluntary efforts

Meng, W, Liu, Q, Zhou, Z et al. (3 more authors) (2015) Recent development of mechanisms and control strategies for robot-assisted lower limb rehabilitation

2.4 Implementing Impedance Control

An impedance controller is chosen for the control of the exoskeleton after careful review of multiple papers. A normal proportional integral derivative controller controls the motion of the end effector in a stiff manner not considering the dynamic interaction with the surroundings.Impedance control aims to achieve the desired mechanical interaction between the robotic equipment and its environment.

While many of the tasks performed by the exoskeleton interacts with its environment such as pushing, touching, carrying sensitive objects and cutting, etc. The implementation of all these tasks require that the exoskeleton, besides realizing the expected position, provide the necessary force either to overcome resistance from the environment, or comply with the environment. Therefore, the exoskeleton in order to interact and contact safely and friendly to humans or to objects in unknown environments, it is necessary to include an interaction control method that adapts the forces exerted on the environment in order to avoid damages the manipulator and the environment. A force control methods can be used on those applications where the desired force or maximum force to exert is known in advance.

A. ALSHAWI1 and S. KİZİR1 "Impedance control of 2dof serial robot manipulator(May 2018)"

2.5 Mathematical Modelling

The exoskeleton for rehabilitation should be kinematically redundant like thehuman arm. The exoskeletons are worn by a human user, and careful exoskeleton design is required so that itmoves with the natural motion of the user and does not compromise their safety. They are typically designedbased on the skeletal system of the human body. The exoskeleton is composed of a set of links connected together by various joints.For selecting reference frames in exoskeleton applications, the Denavit–Hartenberg (DH) convention is very often used. DH convention allows to construct the forward kinematics function by composing thecoordinate transformations into one homogeneous transformation matrix.

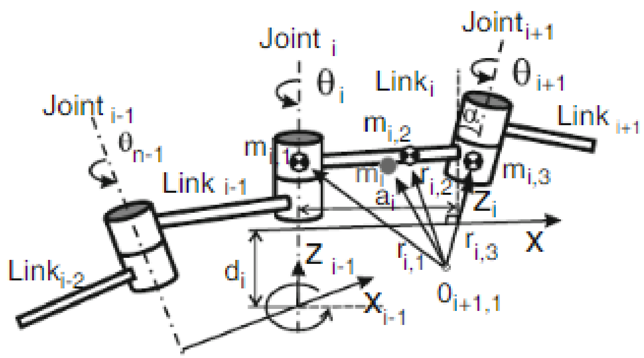

Figure 2.4: The Denavit–Hartenberg convention

S.Głowinski ·T. Krzy˙zynski ·S. Pecolt ·I. Maciejewski"Design of motion trajectory of an arm exoskeleton(August 2014)"

2.6 Objectives:

1. Design a CAD model feasible and efficient upper arm exoskeleton system.
2. Mathematically model the exoskeleton system to obtain the dynamic equations.
3. Test the Model with PID control to observe the stiffness of nominal control techniques.
4. Design an Impedance Controller and Gravity compensation to introduce a sense of compliance to the exoskeleton system with the environment. 5. Run the controller in simulation and observe the results.

CHAPTER 3

METHODOLOGY

3.1 Mathematical Modelling

A two degree of freedom upper arm exoskeleton with one degree of freedom in the shoulder and one degree of freedom in the elbow is modelled using Denavit - Hartenberg convention. Denavit -Hatenberg convention is a formulation that is used to find the position and orientation of the end-effector of a kinematic chain with reference to the fixed frame at the base of the kinematic chain. The first step of the methodology is to design the model of the exoskeleton arm. The model of the upper arm exoskeleton used in this research is shown in the figure 3.1.

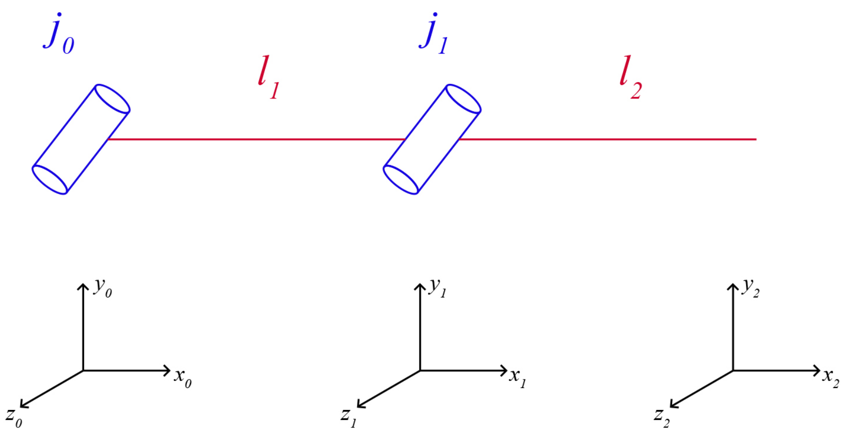

Figure 3.1: Upper Arm Exoskeleton Model

where,
l_0 and l_1 are lengths of link 1 (upperarm) and link 2 (forearm)
j_0 and j_1 are revolute joints of the arm
θ_0 and θ_1 are angular rotations of the revolute joints

The rules for assigning joint frames are as follows:

1. The z-axis is in the direction of the joint axis
2. The x-axis is parallel to the common normal of the z-axis.
3. The y-axis follows from the x- and z-axis by choosing it to be a right-handed coordinate system.

The joint frames are assigned according to the Denavit - Hartenberg convention and parameters are then calculated as per the rules. The parameter values the upper arm exoskeleton are listed in table 3.1.

$Frames$	θ_n	α_n	d_n	r_n
1	θ_1	0	0	l_1
2	θ_2	0	0	l_2

Table 3.1: Denavit - Hartenberg parameters

where,
θ_n is angle about previous z, from old x to new x
α_n is angle about common normal, from old z axis to new z axis
d_n is offset along previous z to the common normal
r_n is length of the common normal. Assuming a revolute joint, this is the radius about previous z.

The parameter values are then substituted in the following matrix. The matrix is also known as Denavit - Hartenberg matrix.

$$A_n = \begin{pmatrix} cos(\theta_n) & -cos(\theta_n)cos(\alpha_n) & sin(\theta_n)sin(\alpha_n) & l_n cos(\theta_n) \\ sin(\theta_n) & cos(\theta_n)cos(\alpha_n) & -cos(\theta_n)sin(\alpha_n) & l_n sin(\theta_n) \\ 0 & sin(\alpha_n) & cos(\alpha_n) & d_n \\ 0 & 0 & 0 & 1 \end{pmatrix} - (3.1)$$

After the substitution of the parameters into the matrix, A homogeneous transformation matrix is obtained by multiplying the Denavit - Hartenberg matrices of each frame. The resulting homogeneous transformation matrix reflects the position and orientation of the exoskeleton arm with respect to the base frame. The homogeneous transformation matrix is given by

$$T_1^4 = A_1\ A_2 = \begin{pmatrix} R_1^4 & o_1^4 \\ 0 & 1 \end{pmatrix} - (3.2)$$

From the homogeneous transformation matrix, we find the position of the end-effector by

$$(\mathrm{x}_2, y_2, z_2) = o_1^4 - (3.3)$$

After completion of all the steps, the final forward kinematic equations of the two degree of freedom upper arm exoskeleton is devised. The final equations for the end effector coordinates for given angles of the joints is as follows

$$x = l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2) \text{ -- } (3.4)$$
$$y = l_1 \sin(\theta_1) + l_2 \sin(\theta_1 + \theta_2) \text{ -- } (3.5)$$

The forward kinematics only gives us a coordinate output for input angles between the links. A Lagrangian - Euler formulation for the two degree of freedom upper arm exoskeleton is derived to get the output angular acceleration for given torque input. The following equation is the general form for any type of manipulator

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta}) + G(\theta) = u \text{ -- } (3.6)$$

where,
$M(\theta)$ is the $n \times n$ inertial matrix of the exoskeleton
$C(\theta, \dot{\theta})$ is the vector of Coriolis and centripetal force
$G(\theta)$ is the vector of gravitation

The final mathematical model of a two degree of freedom upper arm exoskeleton is as follows

$$M(\theta) = \begin{pmatrix} (m_1 + m_2)l_1^2 + m_2 l_2^2 + 2m_2 l_1 l_2 cos(/theta_2) l_1 & m_2 l_2^2 + M_2 l_1 l_2 cos(/theta_2) \\ m_2 l_2^2 + m_2 l_1 l_2 cos(\theta_2) & m_2 l_2^2 \end{pmatrix}$$

$$G(\theta) = \begin{pmatrix} (m_1 + m_2) g l_1 cos(\theta_1) + m_2 g l_2 cos(\theta_1 + \theta_2) \\ m_2 g l_2 cos(\theta_1 + \theta_2) \end{pmatrix} \text{ -- } (3.8)$$

$$C(\theta, \dot{\theta}) = \begin{pmatrix} -m_2 l_1 l_2 (2\dot{\theta}_1 \dot{\theta}_2 + \dot{\theta}_1^2) sin(\theta_2) \\ m_2 l_2 l_1 \dot{\theta}_1^2 sin(\theta_2) \end{pmatrix} \text{ -- } (3.9)$$

3.2 Solid Modelling

A literature survey was conducted on various upper limb exoskeleton related research papers. Different designs and control algorithms used for the control of exoskeleton robots were studied extensively. The technical details of different exoskeletons that are being used in both research and industrial sectors were researched before coming up with a feasible design. The factors of affordability, feasibility, cost and mobility were considered while designing the upper arm exoskeleton.

An exoskeleton arm is designed in Autodesk Fusion 360. The model is rendered with acrylonitrile butadiene styrene (ABS) as the filling material. ABS is chosen as the filling material because, it is easily available, cost effective and the material properties are well suitable for exoskeleton systems. Since the exoskeleton's application is rehabilitation, it is not necessary for the material to withstand large forces. So, ABS as the filling material is the ideal choice. A simple elbow exoskeleton with 1 degree of freedom in the elbow joint is constructed in the CAD environment. The exoskeleton will have two rotary actuators on both sides to control the elbow angle as per the input command. The straps are made of elastic material to accommodate arms of various sizes.

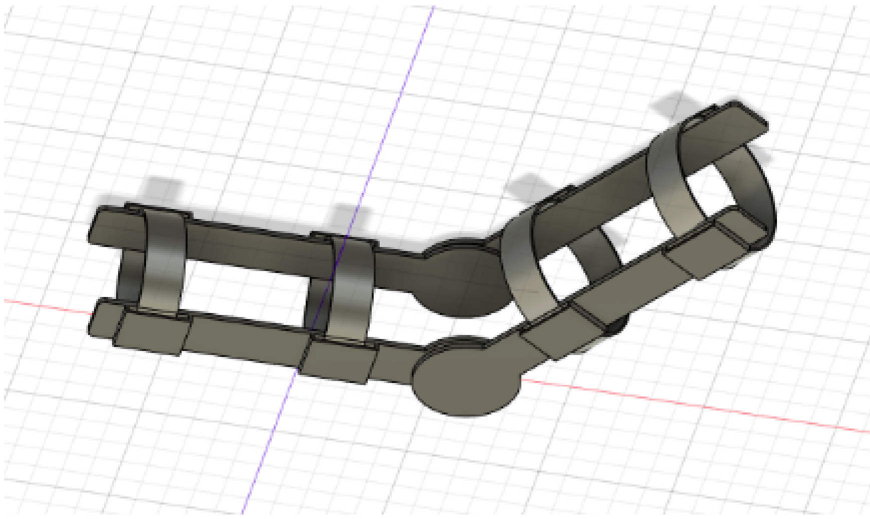

Figure 3.2: Initial CAD design

The presence of multiple actuators at the elbow joint and the absence of support structure in the initial design called up for new improved design. A new CAD of the exoskeleton is designed. The new design has two arm links - lower arm and upper arm - connected together with a rotary joint. The upper arm link is in turn connected to the shoulder link with a rotary joint and the shoulder link is fixed to a support structure for better support. ABS is chosen as the filling material for the CAD in the new design.The new design has better support and actuation compared to the previous design.

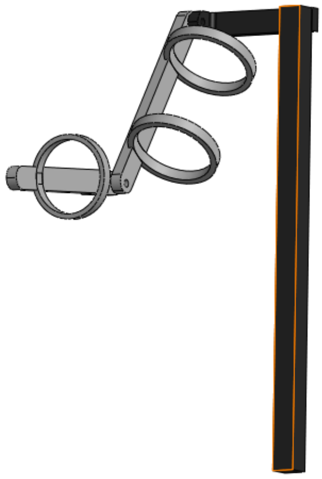

Figure 3.3: Final Design of the upper arm exoskeleton

Human upper arm measurements charts are referred while choosing the parameters for the upper arm exoskeleton. The parameters of an average human arm is used for solid modelling and control, so that the exoskeleton can fit perfectly with a person of average arm measurements. This makes sure that the rehabilitation process progresses smoothly. The parameters used for modelling of the arm are as follows

The parameters,
l is length of the solid part
b is breadth of the solid part
w is width of the solid part
m is mass of the solid part
Ixx is moment of inertia around x axis
Iyz is the product of inertia around y and z axis

The values of the parameters are presented in form of a table, with each row representing the parameters of the solid model and each column represents the solid part of the exoskeleton assembly. The table is given below

Parameter	Forearm	Upperarm	Shoulder Joint	Stand
l (mm)	600	285	300	165
b (mm)	105	105	52	30
h (mm)	105	105	15	30
m (g)	165.633	211.78	89.90	550.80
Ixx (g mm^2)	185917.914	457384.61	16106.51	16565310.00
Ixy (g mm^2)	114.746	25315.47	0.00	0.00
Ixz (g mm^2)	-180393.121	0.81	-22091.09	0.00
Iyx (g mm^2)	114.746	25315.47	0.00	0.00
Iyy (g mm^2)	1199314.959	1548509.17	247991.83	16565310.00
Iyz (g mm^2)	-75.895	5.86	0.00	0.00
Izx (g mm^2)	-180393.121	0.81	-22091.09	0.00
Izy (g mm^2)	-75.895	5.86	0.00	0.00
Izz (g mm^2)	1114520.678	1722971.30	245167.87	82620.00

Table 3.2: Modelling parameters

3.3 Control Strategy

Impedance control is a unique control scheme that is employed to achieve desirable dynamic interaction between a manipulator and its environment. The impedance usually refers to the dynamic relationship between the motion variables of manipulators and the contact forces. For robotic manipulation, the target of impedance control is to control this dynamic relationship to fulfill the requirements of a specified interaction task, such as keeping the contact force always in a preset safe or acceptable range when the robotic equipment is tracking the desired motion trajectory.

A normal proportional integral derivative controller controls the motion of the end effector in a stiff manner not considering the dynamic interaction with the surroundings. When the system interacts with an external object in a rather stiff way with sudden movements, a lot of damage can occur to the wearer of the exoskeleton arm. However, an impedance controller on the other hand controls the force acting in the end effector for a given input motion. The control of the ratio of force and motion gives a motion similar to the motion of the system in a viscous medium. The degree of stiffness in the response can be reduced easily from the control of impedance. This type of response improves the safety of the wearer when his exoskeleton arm comes in contact with the surrounding environment.

Mechanical impedance refers to the dynamic relationship between an input flow and an output effort at the interaction port between a manipulator and its environment. The input flow is the velocity of the manipulator, and the output effort is the resulted contact force. Therefore, in Laplace domain, impedance Z(s) can be directly written as the ratio of the effort (F(s)) to the flow ($\ddot{X}$(s))

$$Z(s) = F(s)/(s) \text{ – (3.10)}$$

The laplace transformation of the equation can be written as

$$sZ(s) = F(s)/X_r(s) \text{ – (3.11)}$$

For a manipulation task, if both F(s) and X r (s) can be controlled properly, an elaborate manipulation can be achieved. But F(s) and X r (s) are not two independent variables, as they must meet the interaction through sZ(s) . In this situation, impedance control was proposed to handle this problem in a novel way. Its strategy is to control Xr(s) and regulate the impedance relation Z (s) as desired so that automatically F(s) could be regulated indirectly by. This is one basic working principle of impedance control. In ordinary cases, the impedance Z(s) is usually described as

$$Z(s) = Ms + B + K/s \text{ – (3.12)}$$

The coefficient matrices M, B, and K represent the desired inertia, damping and stiffness values, respectively, to quantify the impedance. This kind of impedance can be employed to determine the contact force in response to the motion input. The relative displacement $X_r(s)$ can be expressed as the difference between the actual position X(s) and the equilibrium position $X_v(s)$

$$X_r(s) = X(s) - X_v(s) \text{ – (3.13)}$$

Combining the previous equations gives us the following result

$$F(s) = (M_d s_2 + B_d s + K_d)(X(s) - X_v(s)) \text{ – (3.14)}$$

After the inverse Laplace-transformation and the reorganization, this impedance relation- ship can be expressed by differential equation in time domain as

$$M_d\ (\ddot{x} - \ddot{x}_v\ ) + B_d\ (\dot{x} - \dot{x}_V\ ) + K_d\ (x - x_v\ ) = F(t) \text{ – (3.15)}$$

where M_d , B_d , and K_d represent the desired inertia, damping, and stiffness matrices determined by designer, whose dimensions depend on the degrees of freedom; F(t) is the actual contact force vector; x(t) is the actual position vector of the end-effector; $x_v(t)$ refers to the virtual trajectory of the end-effector, which defines a series of virtual equilibrium positions for interaction. When the impedance is specified, the virtual trajectory can be regarded as a reference trajectory used for determining a proper force response to the error between the actual position and the virtual position. If there is no contact, the actual trajectory will approach to the virtual trajectory. However, when the motion of manipulator is constrained, the virtual trajectory is difficult to be reached due to physical limitations. This is why it is named "virtual trajectory."

The impedance control law decides the input for the joint actuators. For a simple robot with only one torque-controlled motor joint, the applied control law on the motor can greatly shape the dynamic behavior of this robot. The control law for impedance control is

$$\tau_{imp} = K(\theta_v - \theta) + B(\dot{\theta_v} - \dot{\theta}) \quad – (3.16)$$

where τ_{imp} is the driving torque generated by the motor; θ and θ_v represent the actual angular position and the virtual equilibrium angular position, respectively; the coefficients K and B can be viewed as the virtual rotational stiffness and damping of the joint, respectively. This control law defines the joint torque in response to the motion of robot, reshaping the dynamics of this joint as a spring–damper system.

When Impedance Control is implemented, the stiffness constant is always set a lower value. The lower value of stiffness constant ensures the compliance of the exoskeleton arm when coupled with an external object. This lower stiffness constant introduces a bias contributed by the gravitation terms in the upper arm exoskeleton dynamic equation. To counter the bias, a gravity compensation input is given alongside impedance controller input. This cancels the gravitation terms in the exoskeleton dynamic equation, thereby reducing the bias in the trajectory. The gravity compensation component is found by analysing the $G(\theta)$ from the system dynamical equation and cancelling the terms that contribute to the bias .The final input for the exoskeleton is given as

$$\tau = \tau_{imp} + \tau_{gc} \quad – (3.17)$$

3.4 Simulation

A nominal PID controller is implemented at initially using Robotics Operating System (ROS). The solid parts designed in Fusion 360 are converted to stereo lithography files. The Gazebo real world physics Simulator and RVIZ visualization tool is compatible with stereolithography files. The converted solid part files are then imported using Universal Robot Description Format (URDF). URDF is a description file to model robots and simulate them in RVIZ visualization tool and Gazebo.

The imported files are assigned reference frames automatically by URDF. The robot model parameters from the solid modelling section is used in the URDF. After completing the description of model in URDF, we create a configuration file with PID coefficients. Finally we run all these files together along with inbuilt PID control plugin to control the two degree of freedom upper arm exoskeleton in Gazebo.

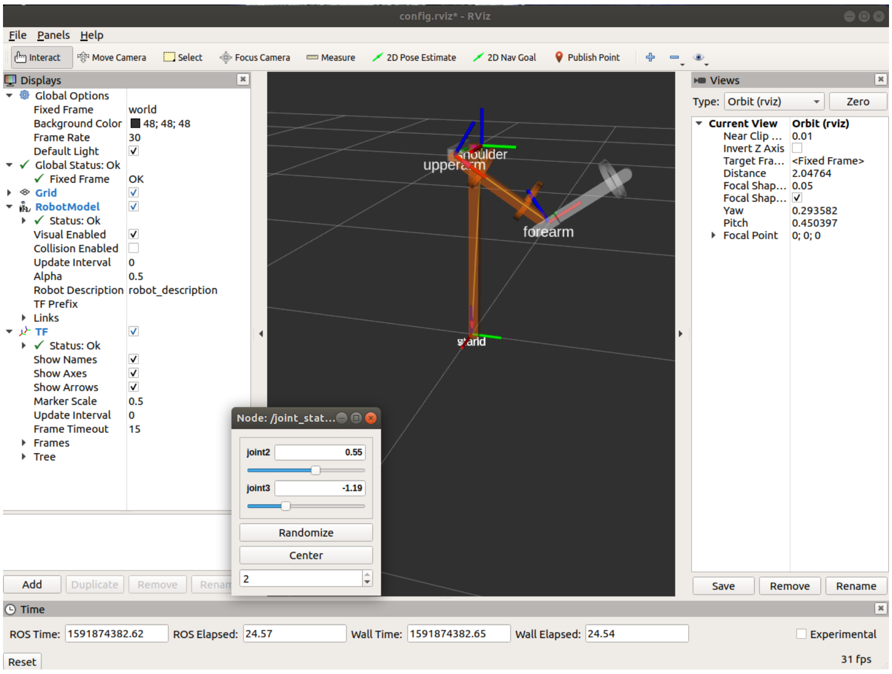

Figure 3.4: The upper arm exoskeleton in RVIZ visualization tool

A stiff control of the arm end effector is observed. This control on contact with the environment is fatal to the users. The coupled dynamics can destabilize the system. To overcome this impedance control simulation was undertaken in MATLAB.

The main reason for using MATLAB instead of ROS is the relative ease in programming and testing. A controller design is generally implemented and tested in MATLAB by control engineers before implementing it in other platforms. MATLAB has extensive set of tools and packages to aid in the process of designing a controller algorithm.

Firstly, all the parameters required for modelling of the upper arm exoskeleton is initialised. The equations from the mathematical modelling section are programmed in MATLAB. An Impedance Controller and a gravity compensation controller is designed and implemented after the model. The initial states are set as per the requirement. The model and control equations are programmed as seperate functions. When the program is run, the states are initialized and the program enters the loop.

Inside the loop the dynamical equations if the upper arm exoskeleton takes the actuator torques as input and gives linear acceleration of the end effector as the output. The angular acceleration is also calculated and both the linear and angular acceleration are integrated to get the respective velocities and displacements. The output states of the system are fed back to the system. The impedance controller gets the states as input to give a output torque for the joint actuator. A gravity compensation term is added along with the impedance controller output and is given as input to the system model

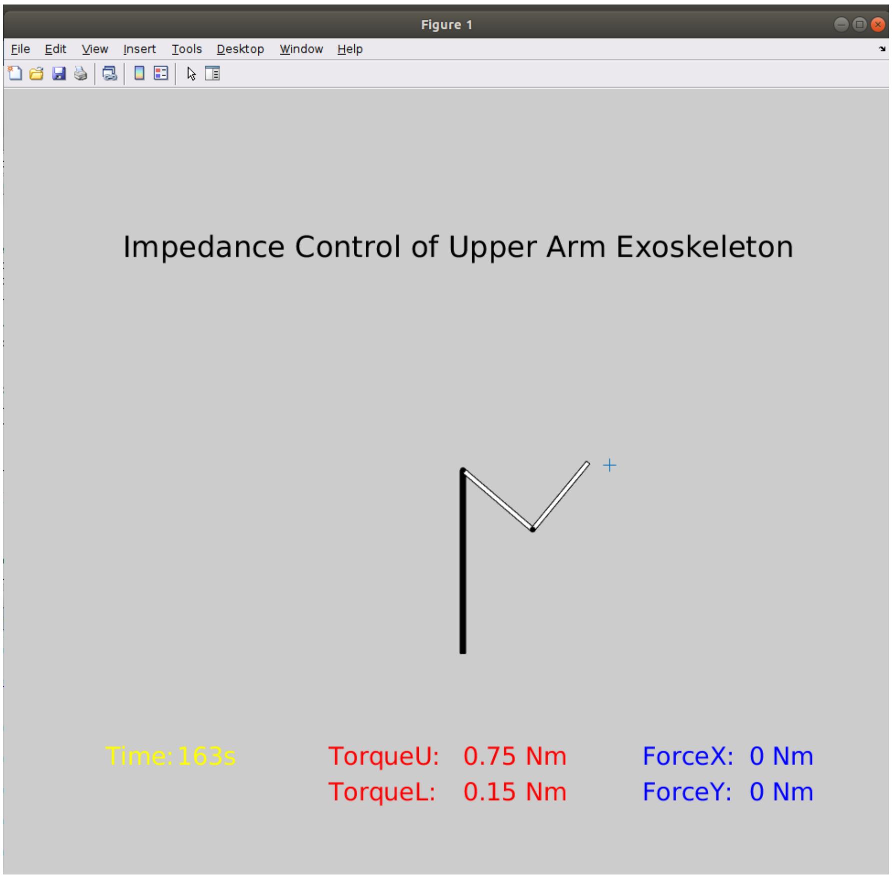

Figure 3.5: Simulation of upper arm exoskeleton in MATLAB

A GUI is designed to visualize the simulation of the exoskeleton arm. The states of the upper arm exoskeleton system are ported to the GUI for visualization of the arm movements. The GUI provides functionalities to set reference coordinates. It also has the functionality to apply force at the end effector. A plus sign in the GUI represents the reference coordinate. The plus sign can be dragged using mouse right button. On changing the reference coordinates, the error is non zero and the impedance control comes into act.

On the other hand force can be applied on the end effector using mouse left button. The amount of drag will decide the magnitude of force. More the mouse is dragged, more force is applied. The GUI not only shows us the configuration of the exoskeleton arm, but also the torque applied by the actuators at both of the joints. The torque that drives the exoskeleton to the desired coordinate is displayed. The time frame and the force applied at the end effector is displayed alongside.

From the GUI it can be observed that the the upper arm exoskeleton has coupled dynamics when the force is applied at the end effector. The impedance control give a sense of compliance to the robot to move around when the force is applied rather than being stiff. The exoskeleton arm then returns back to the set reference set point. The exoskeleton arm strikes a balance in following the reference trajectory as well as complying with the external environment.

CHAPTER 4

RESULTS AND DISCUSSION

The results are obtained from simulating the two degree of freedom upper arm exoskeleton model in the MATLAB for a chosen stiffness constant $K = 10$ and damping constant $B = 8$ after several iterations of tuning. The time response of the results are plotted with y axis being the coordinates and x axis being time. All the graphs have common color coding. Red color line in the reference trajectory and the green lines is response to the reference trajectory by an Impedance controller.

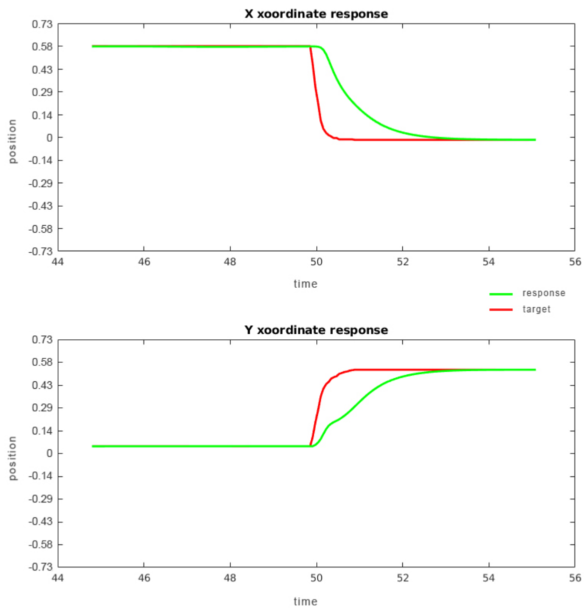

Figure 4.1: Time Response for reference trajectory input

Figure 4.1 shows the response for a reference x coordinate changed from 0.58 meters to 0 meters and the y coordinate changing from 0.4 meters to 0.54 meters. The steady state error is insignificant as the response reaches steady state almost perfectly. The settling time is around 1.5 to 2 seconds. The trajectory tracking is in acceptable standards.

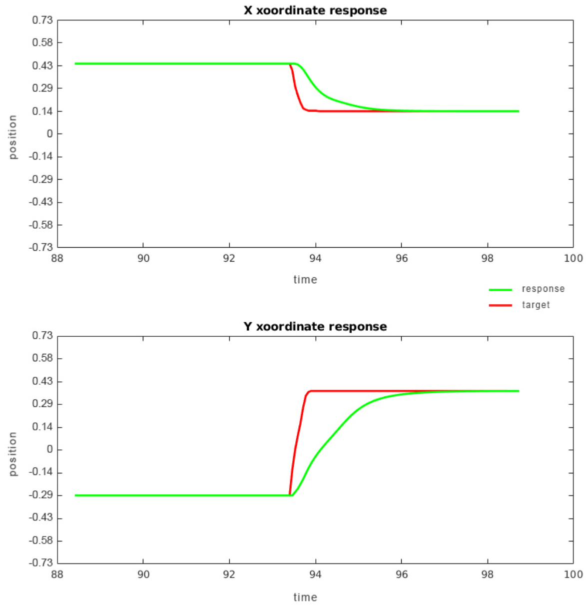

Figure 4.2: Time Response for reference trajectory input

Figure 4.2 shows the response for a reference x coordinate changed from 0.43 meters to 0.14 meters and the y coordinate changing from -0.29 meters to 0.43 meters. The steady state error is insignificant as the response reaches steady state almost perfectly. The settling time is around 2 seconds for the x coordinate and less than 2 seconds for the y coordinate.

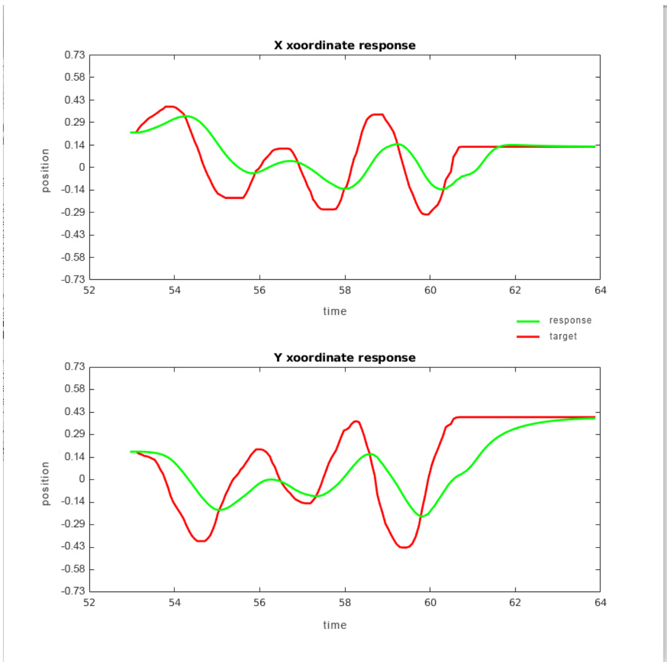

Figure 4.3: Time Response for changing target trajectory

Figure 4.3 shows a time response to a continuously changing set of reference inputs at both the coordinates. The exoskeleton arm manages to follow the reference coordinates up to some level before reaching the steady state

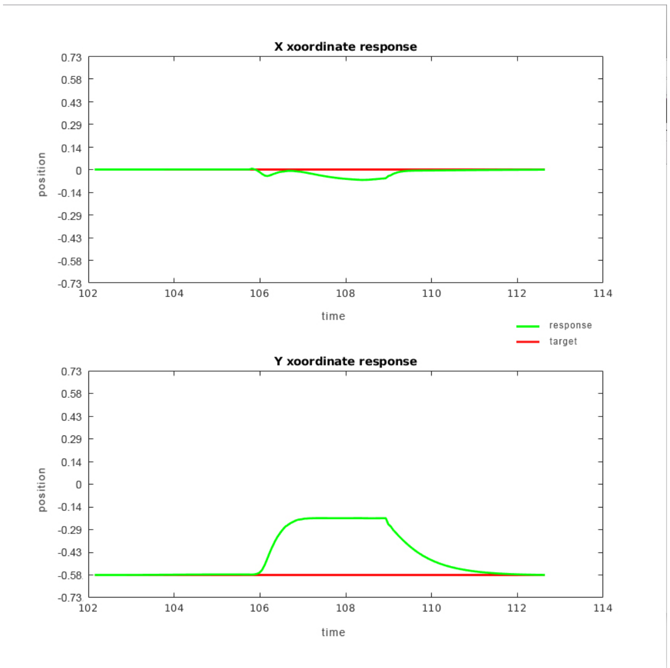

Figure 4.4: Time response when force is applied at the end effector

Figure 4.4 shows a time response when an input force is applied. From the graph, it can be observed that the reference trajectory doesn't change. The force applied at the end effector invokes a response before reaching the reference coordinate. The compliance is clearly observed through the graph. With insignificant steady state error, the settling time of the response is similar to the trajectory tracking result.

Figure 4.5 shows a response to an applies input force. A 13 Nm force is applied at the end effector along the x axis and a -0.46 Nm force is applied along the y axis. The end effector moves complying with the external force before reaching the steady state. The settling time is around 2 seconds for both the coordinates

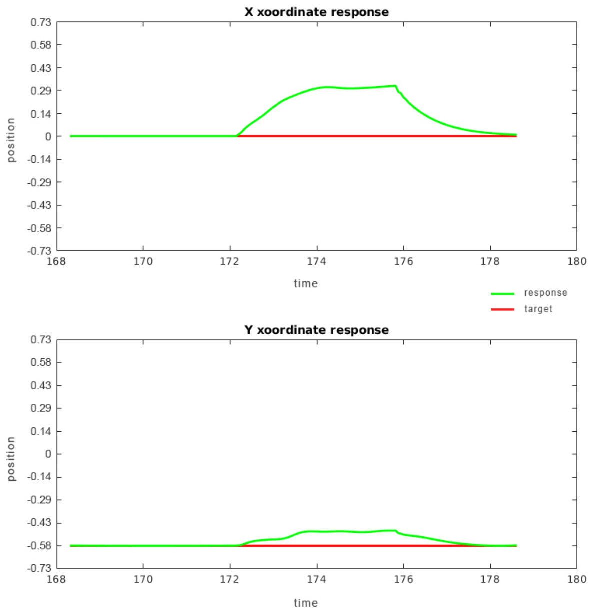

Figure 4.5: Time response when force is applied at the end effector

A detailed analysis was conducted with the GUI created in MATLAB. With various use cases tested, the following results were compiled together after multiple runs. The following table is the results for the impedance control of two degree of freedom exoskeleton

Case	Input	SS Error	Settling Time
X coordinate step input	-0.5 m	0.001 m	2.4 sec
X coordinate step input	0.3 m	0.000 m	1.8 sec
Y coordinate step input	0.7 m	0.000 m	2.6 sec
Y coordinate step input	-0.6 m	0.001 m	2.4 sec
Force applied at end effector along X axis	-2.7 Nm	0.001 m	1.2 sec
Force applied at end effector along X axis	13 Nm	0.000 m	2.1 sec
Force applied at end effector along Y axis	14 Nm	0.002 m	2.3 sec
Force applied at end effector along Y axis	-0.46 Nm	0.001 m	0.42 sec

Table 4.1: Results

Comparing our resutls with the results published Mehdi and Boubaker et al. [16]. The stiffness constant and damping constant they used for their exoskeleton model is $K = 20$ and $B = 5$. The results of their journal is as follows

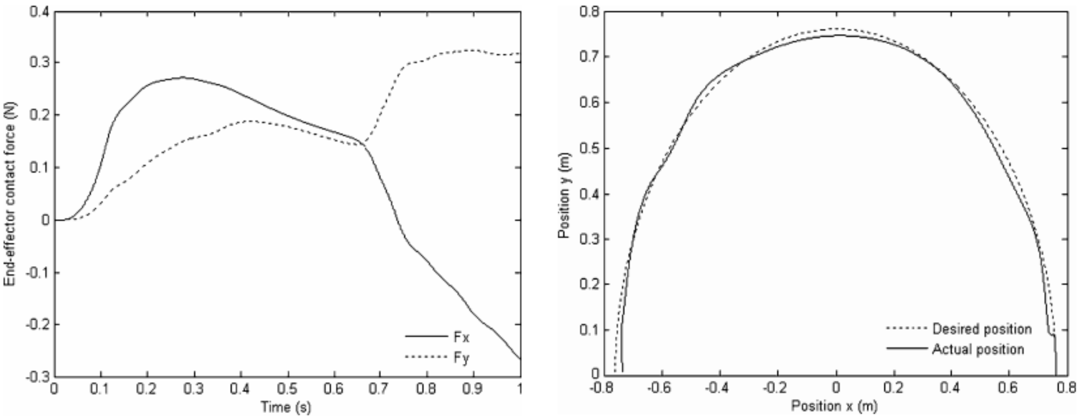

Figure 4.6: End Effector Trajectory under impedance control implemented in [16]

From the results implemented in [16] (Figure 4.6), the response closely follows the curve even after the action of force at the end effector. The stiffness constant $K = 20$ increases the degree of stiffness ensuring the close tracking of the reference trajectory unlike our results. However in our work (Figure 4.4 and Figure 4.5), we proposed a controller with a lesser degree of stiffness $K = 8$. As a result, This sacrifices small losses in trajectory tracking accuracy to introduce compliance between the system and the environment, ensuring the safety of the wearer to the highest priority.

CHAPTER 5
SUMMARY AND CONCLUSION

Wearable exoskeletons are electro-mechanical systems designed to assist, augment, or enhance motion and mobility in a variety of human motion applications and scenarios. The applications, ranging from providing power supplementation to assist the wearers to situations where human motion is resisted for exercising applications, cover a wide range of domains such as medical devices for patient rehabilitation training recovering from trauma, movement aids for disabled persons, personal care robots for providing daily living assistance, and reduction of physical burden in industrial and military applications.

Upper-limb exoskeleton systems have important implication value in motion assistance and rehabilitation applications. The main purpose of the project consisted of designing and manufacturing an exoskeleton to rehabilitation for patients who suffer any type of limitation movements in their hands, caused by an accident or illness. Also, the prototype has a compact, strong and lightweight design, it allows for the possibility of handling it with safety and simplicity. The materials used, ABS stand out especially in the lightness, and the flexibility of the ABS.

The forward kinematics, inverse kinematics and trajectory planning of this device are created based on the Denavit-Hartenberg's parameter model. A 4 degree of freedom arm with 3 degree of freedom in the shoulder and 1 degree of freedom in the elbow is mathematically using Denavit - Hartenberg parameters.The model gives output angles for input coordinates of the exoskeleton system. The calculated matrices are then substituted into the following equation to get the coordinates of the end effector of the 4DOF exoskeleton.

The CAD model of the upper limb exoskeleton is designed in Adobe Fusion 360 solid modelling environment with the parameters decided during the mathematical modelling of the system.The design has two arm links - lower arm and upper arm - connected together with a rotary joint. The upper arm link is in turn connected to the shoulder link with a rotary joint and the shoulder link is fixed to a support structure for better support. ABS is chosen as the filling material for the CAD.

The following control strategies were thoroughly analysed and studied :
1. Position control
2. Force and Impedance control
3. EMG-based control
4. Adaptive control

An impedance controller is chosen for the control of the exoskeleton after careful review of multiple papers. A normal proportional integral derivative controller controls the motion of the end effector in a stiff manner not considering the dynamic interaction with the surroundings.Impedance control aims to achieve the desired mechanical interaction between the robotic equipment and its environment.

The impedance control algorithm is designed to control the force at the end effector by controlling the actuators of the 2 degree of freedom exoskeleton and tuned to get the optimal output response from the system in MATLAB.

CHAPTER 6

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