Isfahan University of Technology
Spring 2019
Supervisor: Saeed Behbahani

CONTROL SYSTEM DESIGN FOR A WRIST AND FOREARM REHABILITATIVE DEVICE

February 26, 2020

Faezeh Haghverd

Mechanical Engineering Department

Abstract

Regarding the upward trend in in the population of affected stroke-survivors, the demand for stroke rehabilitation has increased. Rehabilitation robots have been verified clinically to be effective in terms of long duration and consistent rehabilitation therapies needed for relearning sensorimotor after neurological injury. Coordinated hand and wrist therapy, to improve the performance of activities of daily living, has gained traction recently. To this end, diverse control strategies has emerged for rehabilitating patients with respect to the existing constraints and the level of impairment for each patient. This study was dedicated to design and simulate a control system for a formerly developed 3-DOF hand and forearm rehabilitative device so that this device would be suitable for training and rehabilitating the impaired arm, restoring the ability to perform daily activities. Patient's comfort during the therapy and the quality of interaction between the patient and the device were the main concerns in this study. After modeling the kinematic and dynamic structure of the device, as the first subtask, considering the practical and theoretical requirements, control system is designed and simulated accurately. Finally, to evaluate the designed system, joint position error, joint velocity error, and command force graphs were practiced carefully.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Rehabilitation Robotics for Stroke Patients

As reported by World Health Organization[1], worldwide, cerebrovascular accidents[2] are the second leading cause of death and the third leading cause of disability. Statistics show that 15 million people globally suffer from stroke per year, and 5 million become permanently disabled as a consequence of such complications. Moreover, by an increase in the geriatric population, as well as the invention of effective therapies for acute stroke management, more stroke-survivors tend to live with the resulting disabilities. Damages from stroke, due to physical, cognitive, psychological, emotional and socio-economic consequences, severely affect patients' life and also their families'. To maximize the quality of life for stroke survivors, therefore, efforts to prevent disabilities must be prioritized, along with stroke prevention initiatives. Hence, the demand for stroke rehabilitation is increasing dramatically(1).

Rehabilitation aims to encourage the patients to use the paretic limb in functional tasks and receive training directed toward improving strength and motor control, relearning sensorimotor relationships and improving functional performance. Doing so, task-oriented repetitive movements should be the main subset of rehabilitation programs for patients with impairments due to neurological lesions. To recover the lost brain plasticity and to improve functional outcomes, which are regarded as the main objectives of the rehabilitation, duration and repetition number are the two profoundly significant factors for the therapy. With regards to these factors, classic rehabilitation has evident limitations; being hand-operated, traditional rehabilitation requires full-time operators, and as a consequence it costs high, meaning that the duration of the therapy sessions is generally shorter than the required amount. The heavy reliance of patient compliance on the performance of

[1] WHO
[2] stroke

the therapist is regarded as a further limitation in traditional rehabilitation(2).

Rehabilitation robotics is a branch of robotic science that aims at eliminating the disadvantages of traditional rehabilitation. Utilizing machines in rehabilitation not only increases the number of sessions with consistent repetitions, but also enables the opportunity of assigning one therapist to more than one patient which delivers better performance at lower cost. Robotics also provides the opportunity of objective and quantitative evaluation of patients' performance, during and after therapy. Furthermore, implementing virtual reality, which is not possible in traditional rehabilitation, offers a unique medium to a functional and highly motivating environment, improving the intensity of the therapy and furthering clinical research(2).

The idea of implementing these devices in the treatment of stroke populations has been corroborated by most recent clinical studies involving robotic rehabilitation methods, by proving its efficiency in restoring function for upper extremity movements and motor skills. Hence, robotic rehabilitation has gained significant attention in recent years(2). Therefore, the objective of this thesis was to design and simulate a control system for a previously developed wrist and forearm rehabilitative device. In the following sections, first, the common control methods in rehabilitation robotics are explained briefly. Then, after introducing the target device, the applied methods for this work are summarized.

1.2 Review of Control Strategies for Rehabilitation Robotics

Rehabilitation robots can be classified as either exoskeleton types, where the robot covers and applies forces to several parts of the target limb, or end-effector types, where there is only a single interface between the robot and the patient. In another common classification, they can be categorized into two main groups: passive when the robot only provides support for the motion of the paretic limb during the task, and active when the robot is equipped with actuators. Due to versatile functionality, active systems mainly comprise latest training robots(4).

In rehabilitation systems, assistive, challenge-based and haptic controllers are regarded as the most common strategies.

1.2.1 Assistive Controllers

Assisted training uses external physical assistance, such as exoskeletons, to support the patient in accomplishing the desired task during the therapy. This type of training is used particularly for extensively feeble patients. therefore, to perform the specified task, the patient is completely inactive and the robot moves the muscles in the desired trajectory. In other words, active devices are used to develop passive exercises, so that the patients themselves are not required to make an effort. Another type of assistive controller is called passive assistants, an impedance-based assistance. In this type of training, patients mainly make the effort to move the paretic limb in the desired path, while the machine is completely passive. However, when the patient is unable to finish the task or deviates from the course, the robot intervenes by applying restoring forces to navigate the movement through the specified path. This class of controlled robots are also called assist-as-needed[3] systems, since the robot only assists the patients if they could not finish the intended task(5).

1.2.2 Challenge-based Controllers

The challenge-based controllers in some ways make the training difficult, as opposed to the assistive controllers, which make it simpler for patients. In this strategy, in fact, to promote exertion of effort, the difference between the actual and the desired trajectories increases. This type of strategy includes providing resistance to the patient's movement and error augmenting control algorithms(5).

1.2.3 Haptic Controllers

In rehabilitation, haptic devices may be used as an interface to virtual environments in order to simulate real-life situations. In fact, by the combination of robotics and virtual environments, haptic systems provide an efficient and, at the same time, a stimulative platform to recover patients with neurological impairment. Virtual environments, in these types of devices, can provide simulations of real-life situations to establish an appealing and appropriate context to stroke therapy, and automatically grade the difficulty level, promoting therapy efficiency(5).

1.3 Target Device

The formerly developed device used in this study is a 3-DOF exoskeleton-type robot that matches wrist movements and elbow rotation, consisting of three revolute joints forming a parallel mechanism. Exoskeleton, in fact, is an electromechanical structure designed according to the shape and the function of the human body. These robots provide support to human body motion, aiming to train muscle movements or assisting in injury recovery. Furthermore, exoskeleton robots, merge machine's power and human intelligence, leading to enhancement of, both, machine intelligence and operator power(3).

This robot was designed based on the structure of the wrist and elbow. The movements of wrist and rotation of elbow are measurable and could be transferred to a computer for further processing.

[3] AAN

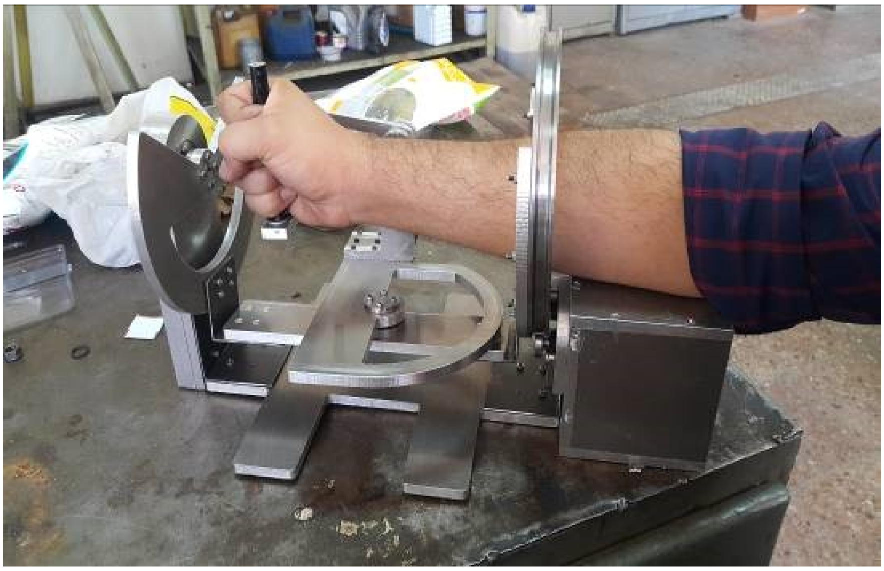

Figure 1.1: The device

In fact, the design of the device was inspired by existing upper-extremity rehabilitation robots, such as OpenWrist, a 3-DoF exoskeleton for coordinated hand wrist rehabilitation, and the 3-DoF Wrist-Gimbal developed for forearm and wrist rehabilitation. Range of motion[4] is regarded as one of the crucial factors in the design and evaluation of rehabilitation systems, which must be complied with the ROM of each joint of the human hand. To evaluate the device design, a comprehensive comparison between the device and ADL, an abbreviation for Activities of Daily Living[5], in ROM is given in table 1.1(6). As can be seen, the robot exceeds almost all the requirements of ADL in ROM. The overall weight of the machine is 3.6 kg, made of aluminum and its bearing joints give it acceptable friction and flexibility.

Table 1.1: Range of Motion [deg](6)

	ADL	Device
PS	150	180
FE	115	135
RU	70	70

1.4 Wrist and Forearm Movements

This 3-DoF mechanism covers 2 degrees of wrist movements and a degree of elbow rotation. Each of these hand degrees are briefly described below(7).

[4]full movement potential of a joint(ROM)

[5]Term used in healthcare refers to people's daily activities

1.4.1 Hand Pronation/Supination

Supination and pronation are terms used to describe forearm rotation, which is referred to by the abbreviation of PS. The movement is explained in figure 1.2. In fact, when the palm or forearm faces up, it is called supinated, and when the palm or forearm faces down, it is considered pronated.

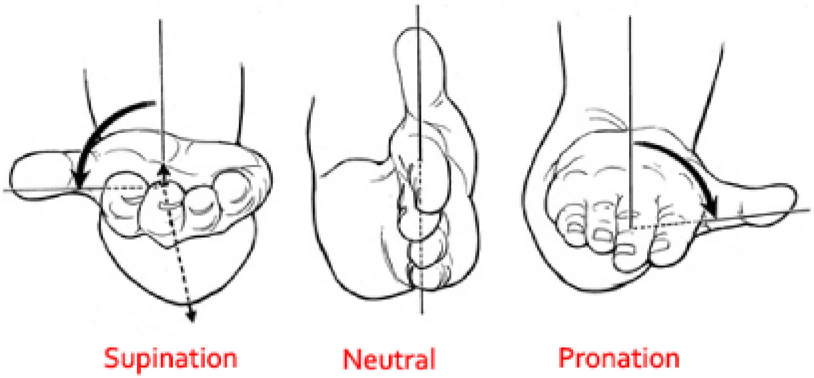

Figure 1.2: PS Movement

1.4.2 Wrist Flexion/Extension

Flexion and extension are movements which are regarded as one of the wrist's degrees of freedom, referred to by the abbreviation of FE. Wrist flexion is the action of bending the hand down at the wrist, so that the palm faces in toward the arm, while extension is to move the hand in the opposite direction. The movement is described in figure 1.3.

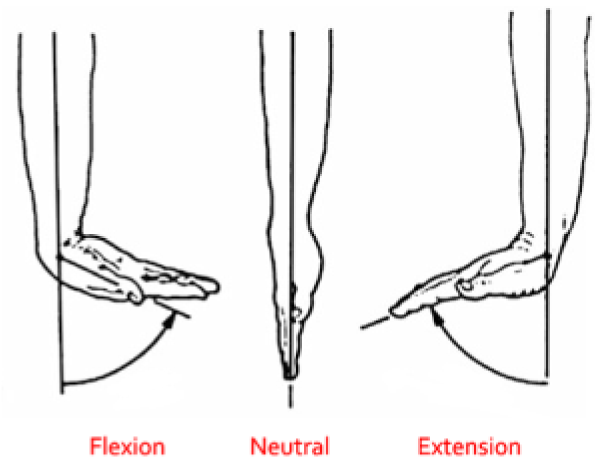

Figure 1.3: FE Movement

1.4.3 Wrist Abduction/Adduction

Adduction of the wrist which is defined as moving a hand toward the body around the wrist when the arm is at the person's side, is also called ulnar deviation. Abduction, on the other hand, is referred to the movement of the hand from the body, and is also called radial deviation. Figure 1.4 demonstrates a schematic of such movements, refered to by the abbreviation of RU.

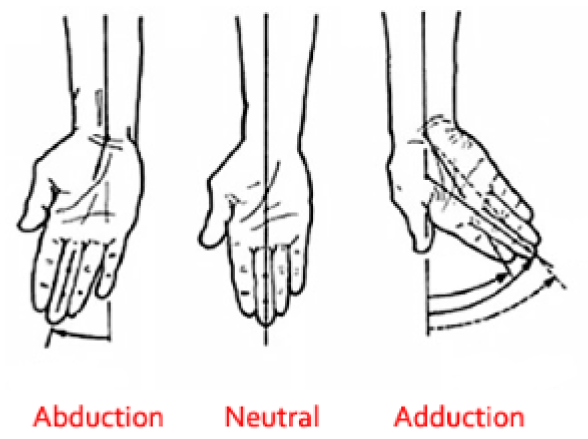

Figure 1.4: RU Movement

1.5 Thesis Outline

This thesis is structured as follows. Chapter 2 details the kinematic and dynamic modeling, utilizing Denavit–Hartenberg method and Newton-Euler approach respectively. Chapter 3 describes the procedure of selecting, designing and simulating the controller through the Simulink software. Ultimately, chapter 4 provides a brief analysis of the results of the control system in the form of joint position error, joint velocity error, and command force charts, evaluating the designed system, and it ends by providing recommendations for future studies.

Chapter 2

Modelling the Device

In this chapter, as the first subtask, kinematic and dynamic modeling of the device are extracted, utilizing Denavit–Hartenberg method and Newton-Euler approach respectively.

2.1 Kinematic Structure

The kinematic structure of the device is modeled using the Denavit–Hartenberg convention detailed in (8). In doing so, with regards to DH notation, reference frames are attached to the links. Figure 2.1 Shows each joints' axis of rotation and the chosen direction of positive Z axis. As all joint axes intersect incidentally, to keep as many parameters in the DH table as possible equal to zero, the origin of all reference frames, that of joints' and base, are placed at the intersection point. Afterwards, the X axes of the reference frames are assigned, also, in a way to keep as much as parameters equal to zero.(4)

DH parameters, , d, a, , are extracted for joints number 1 to 3, as shown in the table 2.1.

Table 2.1: DH parameters

i	a_i	$\alpha_i[rad]$	d_i	$\theta_i[rad]$
1	0	$-\pi/2$	0	q_1
2	0	$\pi/2$	0	$\pi/2 - q_2$
3	0	0	0	q_3

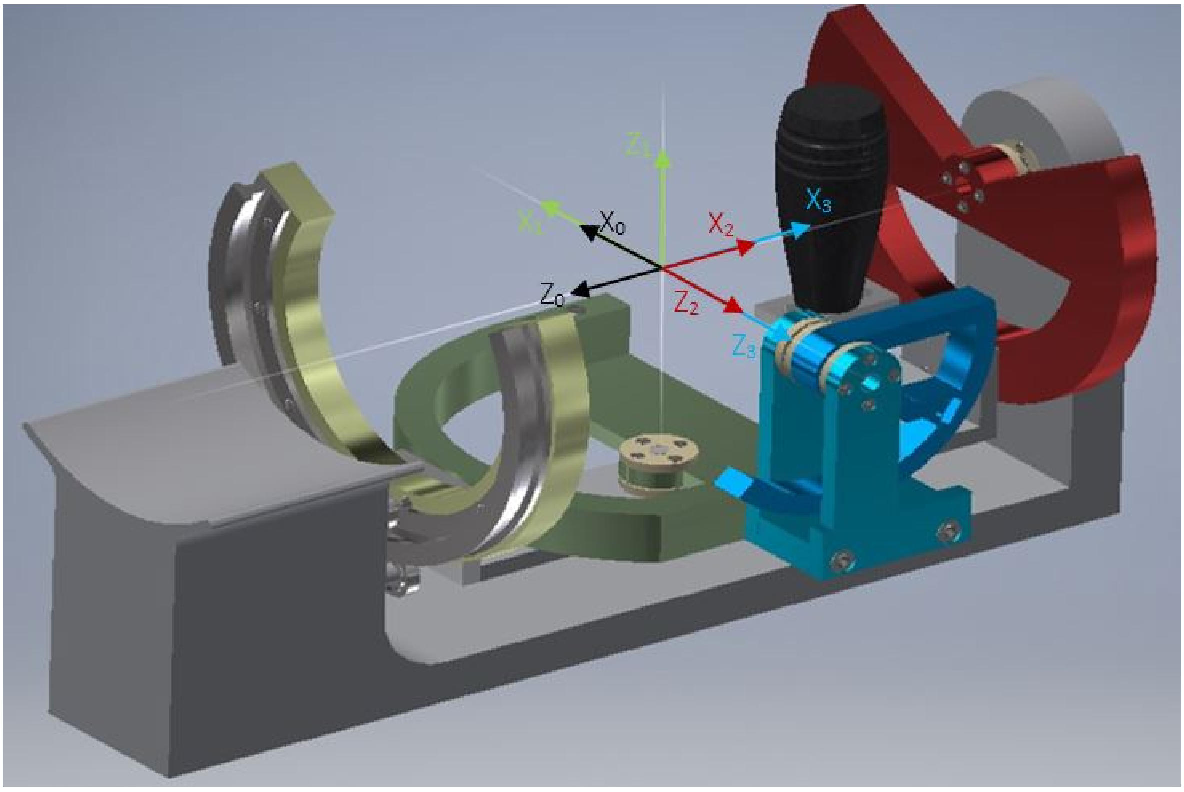

Figure 2.1: Assigned reference frames to each link

Using the table 2.1, the transformation matrix from frame {i} to frame {i-1} is computed with

$$T_i^{i-1} = \begin{bmatrix} cos(\theta_{\mathrm{i}}) & -sin(\theta_{\mathrm{i}})cos(\alpha_{\mathrm{i}}) & sin(\theta_{\mathrm{i}})sin(\alpha_{\mathrm{i}}) & a_{\mathrm{i}}cos(\theta_{\mathrm{i}}) \\ sin(\theta_{\mathrm{i}}) & cos(\theta_{\mathrm{i}})cos(\alpha_{\mathrm{i}}) & -cos(\theta_{\mathrm{i}})sin(\alpha_{\mathrm{i}}) & a_{\mathrm{i}}sin(\theta_{\mathrm{i}}) \\ 0 & sin(\alpha_{\mathrm{i}}) & cos(\alpha_{\mathrm{i}}) & d_{\mathrm{i}} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.1}$$

Ultimately, given T_3^2, T_3^2 and T_1^0, the direct kinematic function is computed as

$$T_3^0 = T_1^0 T_2^1 T_3^2 \tag{2.2}$$

That yields the pose[1] of the end-effector frame with respect to the base frame.

Given the presented equations, forward kinematics function for the device is extracted using MATLAB. To do so, a function where DH parameters are given as input, was provided. and the transformation matrix from the end-effector frame to the base frame, and geometric Jacobean were computed in the output.

[1] position and orientation

2.2 Dynamic Modelling

The manipulator dynamic is modeled symbolically using the iterative dynamic algorithm of Newton-Euler in MATLAB, computing the Equation of Motion (9). First, velocity and acceleration are computed for each link iteratively, from link 1 to link 3. Afterwards, joint torques as well as the interaction forces and torques are computed recursively, starting from link 3 and ending at link 1. The output is resulted in the form of

$$T = M(\theta)\ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) \tag{2.3}$$

where $M(\theta)$ is a 3×3 mass matrix, $V(\dot{\theta}, \theta)$ is a 3×1 vector including centrifugal and Coriolis terms, and $G(\theta)$ is a 3×1 vector of gravity terms.

Then, torques due to reflected actuator rotor inertias and nonrigid body effects are considered as

$$T_{\text{m,ref}} = j_{\text{m,ref}} \times \ddot{\theta} \tag{2.4}$$

$$T_{\text{B}} = B \cdot \times \dot{\theta} \tag{2.5}$$

$$T_{\text{f}_\text{k}} = f_{\text{k}} \cdot (\dot{\theta}) \tag{2.6}$$

where

$$j_{\text{m,ref}} = [j_{\text{m}_1} \eta 1^2, j_{\text{m}_2} \eta 2^2, j_{\text{m}_3} \eta 3^2] \tag{2.7}$$

$B(\theta)$ is a 3×1 vector including viscous damping coefficients, and f_k is a 3×1 vector of kinetic friction parameters.

Adding the above torques, the resulting EOM is computed symbolically as (6)

$$T = M(\theta)\ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) + j_{\text{m,ref}} \times \ddot{\theta} + B \cdot \times \dot{\theta} + f_{\text{k}} \cdot (\dot{\theta}) \tag{2.8}$$

Mass parameters for each link is extracted from the designed CAD drawings as given in the table 2.2.

Table 2.2: Dynamic parameters for each joint

i	M[kg]	I_{cxx}	I_{cyy}	I_{czz}	I_{cxy}	I_{czy}	I_{cxz}
1(PS)	1.915	9992.2	31788.9	3446.1	1065.7	0	0
2(FE)	0.565	3068.8	3171.4	1183.9	11.1	-559.8	-559.8
3(RU)	0.391	1233.1	986.4	665.6	-143.7	353.2	287.1

Since the coefficients of b and f_k are computed empirically, they were extracted from the paper on the OpenWrist device, shown in table 2.3 (6).

Table 2.3: b and f_k coefficients for each joint(6)

i	1(PS)	2(FE)	3(RU)
b	0.0252	0.0019	0.0029
f_k	0.1891	0.0541	0.1339

Considering the available resources, the RE 30 EB engine was selected from the RE series of the famous Maxon engines, and the related parameters are extracted from datasheets (11).

Chapter 3

Control System Design

In this chapter, a thorough description of the design and simulation procedure of the control system in Simulink is presented. High repetition number is considered a key factor contributing to a successful therapy in educating the patient on sensorimotor skills. To apply the effective common strategy of assistive rehabilitation, as previously explained, the patient is required to move the paretic limb, i.e. hand in this device, in a specified path from an initial to a final assigned posture, and frequently repeat this task. To do so, motion control was applied by designing an inverse dynamics controller in joint space.

The main focus in rehabilitative systems is to assist the patient in completing the desired tasks to improve the paretic limb's strength and motor control; hence, accuracy in the control system can be compromised, prioritizing patient's comfort. Therefore, flexibility was regarded as one of the prominent factors in designing this control system, which was achieved by reducing the rigidity of the system.

3.1 Applying Motion Control Using Inverse Dynamics Controller

General scheme of this control cycle is depicted in figure 3.1 First, the trajectory block generates the desired path in the joint space, using the timing law with trapezoidal velocity profile. Then, after comparing with the current position of the robot, the output is entered the controller block as an error.

Given the error vectors, current, and desired position and velocities, the controller computes the command force which is the applied torques to the joints, and derives it to the next block where robot and hand is modelled as a subsystem. This block, feeds each joint position and velocity, q and $\dot{q}$, back into the cycle.

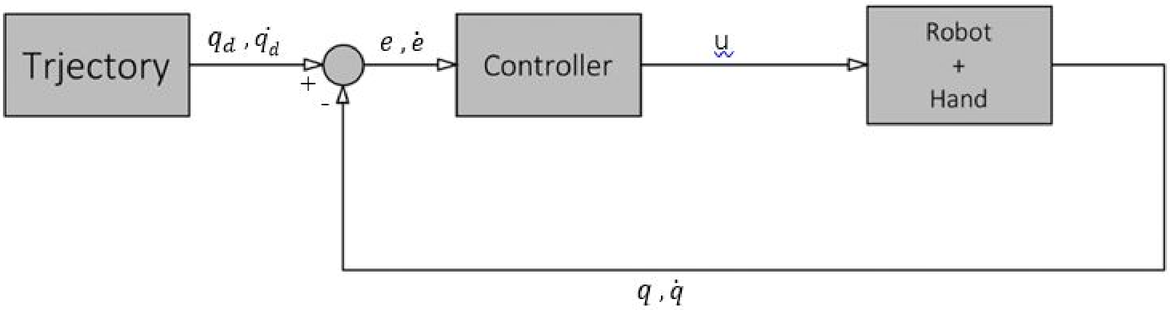

Figure 3.1: General scheme of the designed control system

Each block is explained accurately in the following pages. Figure 3.3 shows the simulated control cycle in the Simulink environment.

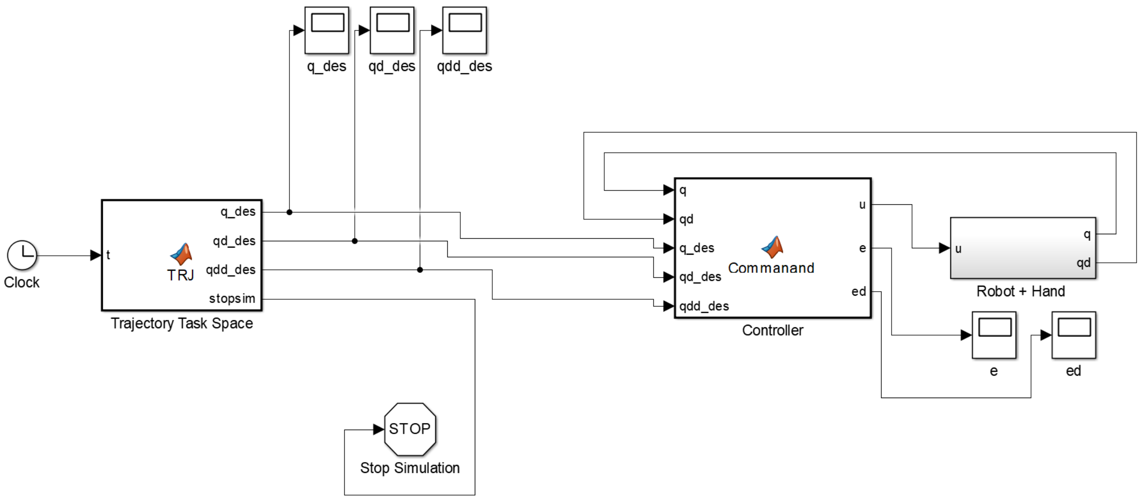

Figure 3.2: The simulated system in Simulink

3.2 Trajectory Block

In joint space, trajectory planning algorithms generate time sequence of values which describes the joint variables so that the manipulator is taken from the initial to the final configuration, with respect to the imposed constraints. Timing laws of blended polynomial type, a frequently used method in industry applications, is regarded as a common approach for generating trajectories. As the main feature, these types of algorithms allow access to velocity and acceleration which provides an opportunity to directly verify whether or not the physical mechanical manipulator is capable of supporting the movement(8).

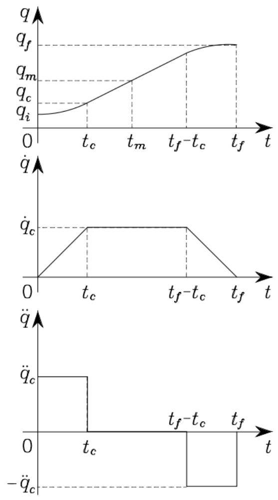

Figure 3.3: Characterization of a timing law with trapezoidal velocity profile in terms of position, velocity and acceleration(8)

In this study, a trapezoidal velocity profile is assigned, in which initial phase is traveled in a constant acceleration motion, followed by cruse velocity, and constant deceleration in the final phase. This algorithm results in a trajectory of a linear segment connected by two parabolic segments to the final and initial positon. For the given time of t_f, the initial and final position of q_i and q_f, maximum permissible velocity of $\dot{q}_c$, equation of computing the position, velocity and acceleration of the joints versus time, with respect to this algorithm, will be presented(8).

$$TL = |q_f - q_f| \tag{3.1}$$

$$T\ddot{q} = \frac{\dot{q}_c^2}{T \times \dot{q}_c - L} \tag{3.2}$$

$$t_c = \frac{\dot{q}_c}{\ddot{q}_c} \tag{3.3}$$

$$q(t) = \begin{cases} q_i + \ddot{q}_c t^2 & 0 \leq t \leq t_c \\ q_i + \frac{1}{2}\ddot{q}_c t_c (t - \frac{t_c}{2}) & t_c \leq t \leq t_f - t_c \\ q_f - \frac{1}{2}\ddot{q}_c (t_f - t)^2 & t_f - t_c \leq t \leq t_{fc} \end{cases} \tag{3.4}$$

3.3 Controller Block

Another approach to control a manipulator is to determine generalized forces for each joint, torque for revolute joints and force for prismatic joints, for the equation 3.5 to be true, where $q_d(t)$ is used to describe values related to the desired trajectory.

$$q(t) = q_d(t) \tag{3.5}$$

Centralized control algorithms allow taking advantage of knowledge of manipulator dynamics, partially or completely, to generate compensating torques for nonlinear terms. In this case, inverse dynamics controller, a commonly used centralized control method, is selected to be applied. Inverse dynamics controller or computed-torque control performs an exact linearization of system dynamics by directly compensating V, g, T_b, and T_{f_k} terms(8). To do so, the torque command is computed as

$$\tau = M(\theta)[\ddot{q} + k_v\dot{\tilde{q}} + k_p\tilde{q}] + V(q,\dot{q}) + g(q) + B \cdot \times\dot{q} + f_k \cdot (\dot{q}) \tag{3.6}$$

$$\tilde{q} = q_d - q$$

$$\dot{\tilde{q}} = \dot{q}_d - \dot{q}$$

In fact, substituting this torque command 3.6 into the identified dynamic system 2.8 gives the dynamics of the closed-chain error in the homogeneous second-order differential equation as

$$\ddot{q} + k_v\dot{\tilde{q}} + k_p\tilde{q} \tag{3.7}$$

where $\dot{\tilde{q}}$ and $\tilde{q}$ express position and velocity error which converge to zero with a speed that depends on the defined matrices k_p and k_v.

Hence, in this block, for the given desired acceleration, velocity and configuration of each joint and also current joint position and velocities, utilizing the provided function, dynamic terms are computed and substituted in 3.7 to compute the control torque in the output.

3.4 Plant Block

This block, in fact, is a subsystem which models the device in interaction with the patient's hand. First, the torque command is applied to the system by substituting in the identified dynamic model 3.8 to compute $\ddot{q}$ which represents instantaneous acceleration of each joint. Then, by two times integration, velocity and configuration of each joint is computed in the output of the subsystem as a feedback to the closed-chain.

$$\ddot{q} = M^{-1}(q)(\tau - (V(q,\dot{q})G(q) + B \cdot \times\dot{\theta} + f_k \cdot \times sgn(\dot{\theta}) + \tau_e)) \tag{3.8}$$

τ_e is the torque applied to the manipulator from the environment, added to the dynamic system 2.8. In this case, the hand acts as the environment in which the grip force is excerted to the manipulator's end-effector which is the provided knob. To compute the grip force, the data of a clinical study carried out by Dr. Burssens, et al. is used (10). By collecting the grip force data from 30 healthy men in different wrist positions, they obtained 3.9 which describes the relationship between the grip force and the wrist position. Considering the arm vector connecting the grip force to the end-effector, τ_e is computed for each current joint position vector that enters the system block.

$$f(q) = -4.98 + \frac{16.92}{(1 + \frac{q}{8.59})^{2.24}} \tag{3.9}$$

Figure 3.4 shows the simulated subsystem in Simulink.

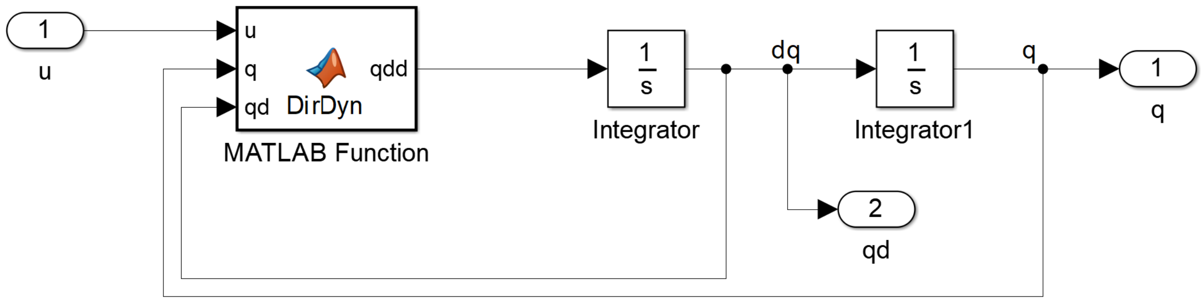

Figure 3.4: The simulated subsystem in Simulink environment

Chapter 4

Results and Recommendations

The primary objective of this study was to design and simulate a control system for a previously developed wrist and forearm rehabilitative device so that this device would be suitable for training and rehabilitating the impaired arm, restoring the ability to perform daily activities. In this study, main concerns were patient's comfort during the therapy and the quality of interaction between the patient and the device (HRI). During the research procedure, the first challenging task was to model the device, using common robotic methods. Also, works done by Dr.Burssens were utilized for computing the grip force in order to consider the interaction between hand and device. To design a control system which covers the assistive approach, inverse dynamic method were selected.

The designed system, ultimately, reached a reasonable accuracy and the simulated interaction between the patient and the device got qualified enough so that it would be suitable to be implemented on the device.

In this chapter, the results of the simulation presented in the previous chapter are illustrated by error graphs, and analyzed briefly. In the end, suggestions for following studies are presented.

4.1 Generated Trajectory Graphs

The generated desired trajectory, for the given time of 10 seconds and the maximum allowed velocity of 0.2, are illustrated in terms of position, velocity and acceleration for all the three joints, in figure 4.1,4.2 and 4.3 respectively

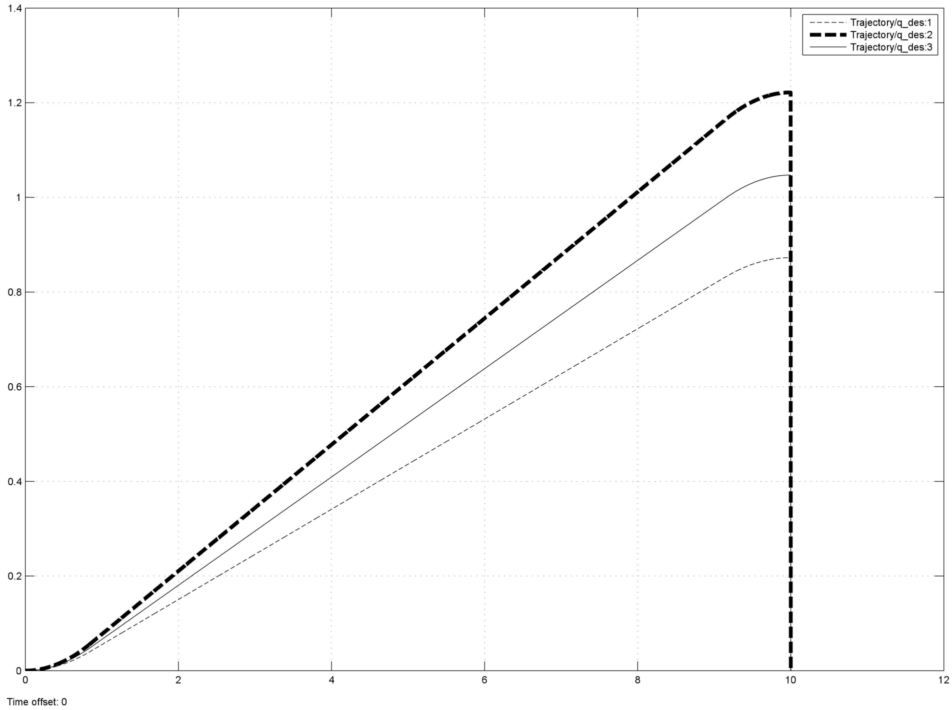

Figure 4.1: Generated desired position profile for 1:PS, 2:Ru and 3:FE joints (rad) against time (second)

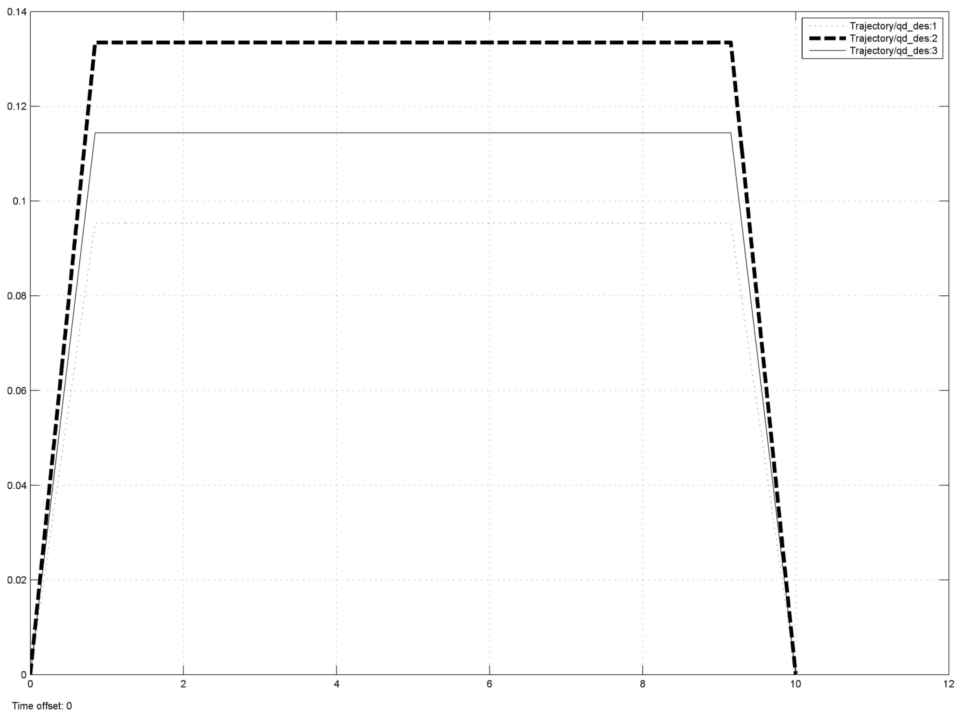

Figure 4.2: Generated desired velocity profile for 1:PS, 2:Ru and 3:FE joints (rad/s) against time (second)

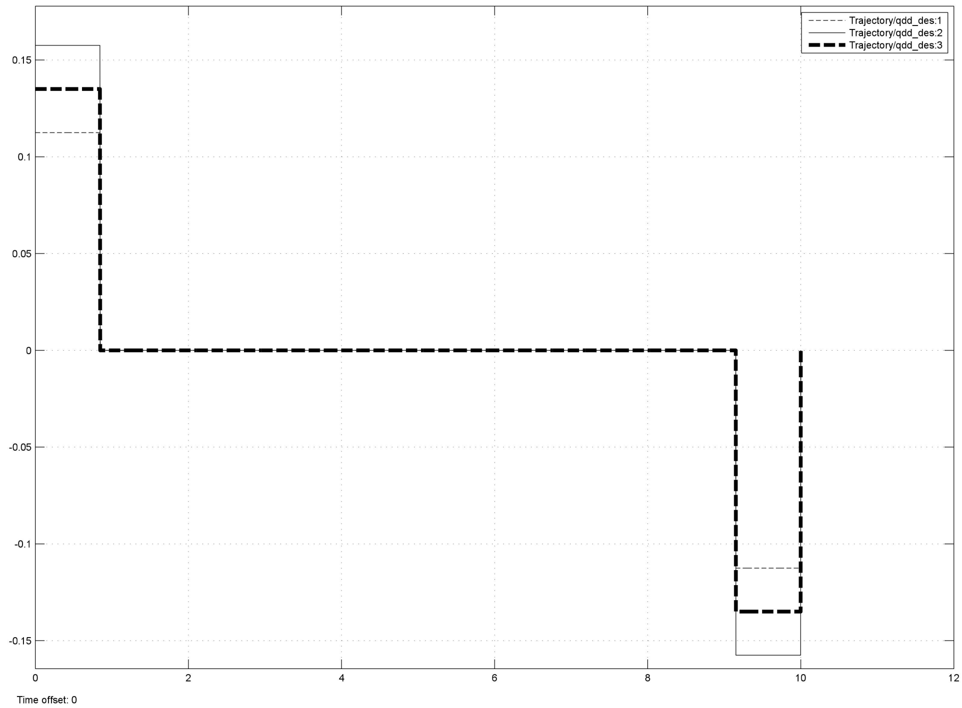

Figure 4.3: Generated desired acceleration profile for 1:PS, 2:Ru and 3:FE joints (rad/s^2) against time (second)

4.2 Error and the Torque Command Graphs

After simulating the movement under the control of the designed ID controller, for the total time of 10 seconds, the resulted joint position and velocity errors graphs are given in the figure 4.4 and 4.5, while the torque command versus time is illustrated in figure 4.6. In this controller, considering the maximum allowed error and given the need for a flexible and low-rigid system in cooperation with patient, evaluating and modifying iteratively, control coefficients of k_p=4000 and k_v=1000 are defined ultimately.

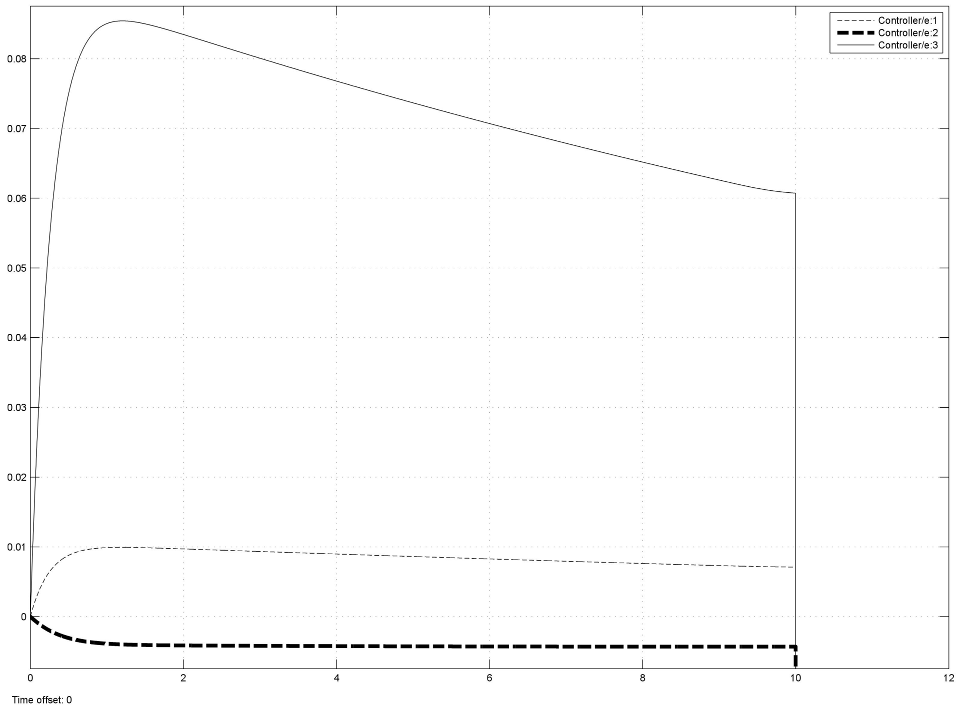

Figure 4.4: The position error for 1:PS, 2:Ru and 3:FE joints (rad).Difference between desired and real trajectories against time (second)

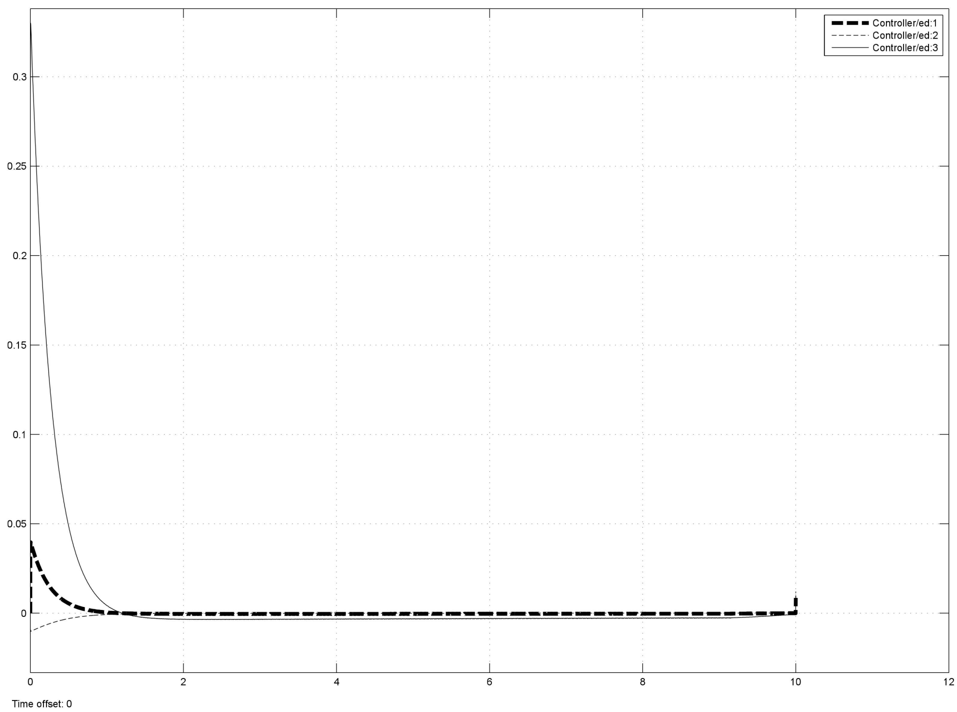

Figure 4.5: The velocity error for 1:PS, 2:Ru and 3:FE joints (rad/s).Difference between desired and real velocity profiles against time (second)

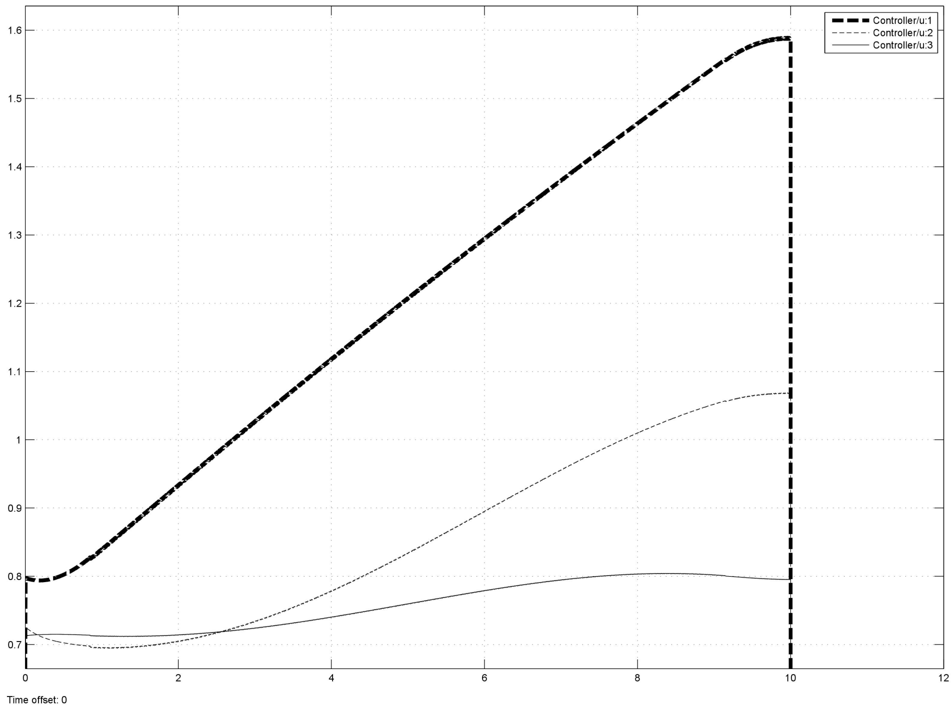

Figure 4.6: The computed command torque (N.m) for each joint of 1:PS, 2:Ru and 3:FE against time (second)

4.3 Recommendations

Considering the simulation phase done successfully and accurately, practical implementation must be prioritized for the following steps. By equipping the device with actuators and encoders, the designed controller algorithm can be performed for the purpose of utilizing the device for rehabilitating patients with neurological impairments, mainly post-stroke patients, as the primary objective of developing this 3-DOF coordinated hand-wrist exoskeleton.

Previously explained strategies of challenge-based and haptic controllers can be also implemented to this device in following studies, aiming to promote the efficiency for patients with voluntary control over the paretic limb and providing a motivating interface for elderly and young patients.

Bibliography

[1] A. Gupta, M. K. O'Malley " Design, Control and Performance of RriceWrist: A Force Feedback Wrist Exoskeleton for Rehabiliation and Training ", The International Journal of Robotics Research, Vol. 27, No. 2, pp. 233–251, February 2008.

[2] A. U. Pehilvan, "Design and Control of an Exoskeletal Rehabilitation Device for Stroke and Spinal Cord Injury Patients", 2011.

[3] E. Pezent, C. G. Rose, A. D. Deshpande and M. K. O'Malley, "Design and Characterization of the OpenWrist: A Robotic Wrist Exoskeleton for Coordinated Hand-Wrist Rehabilitation," International Conference on Rehabilitation Robotics (ICORR) QEII Centre, 17-20 July 2017.

[4] H. J. Asl, T. Narikiyo, M. Kawanishi, "An Assist-as-Needed Control Scheme for Robot-Assisted Rehabilitation", American Control Conference,E 2017.

[5] A. Ali, S. F. Ahmed, M. K. Joyo, A. Malik, M. Ali, K. Kadir, Z. M. Yusof, "Control Strategies for Robot Therapy", Sindh University Research Journal, 2016.

[6] E. Pezent, C. G. Rose, A. D. Deshpande and M. K. O'Malley, "Design and Characterization of the OpenWrist: A Robotic Wrist Exoskeleton for Coordinated Hand-Wrist Rehabilitation," International Conference on Rehabilitation Robotics (ICORR) QEII Centre, 17-20 July 2017.

[7] A. Gup, "Design and Analysis of an Adjustable Wrist Rehabilitation Robot," 2014.

[8] B. Siciliano, "Robotics; Modeling, Planning and Control", Int. J. Heat and Mass Transfer, Vol. 30, No. 8, pp-1709-1719, 1987

[9] J. J. Craig, Introduction to Robotics: Mechanics and Control (3rd Edition). Pearson, 2004.

[10] A. Burssens, N. Schelpe3, J. Vanhaecke, M. Dezillie, F. Stockmans, "Influence of wrist position on maximum grip force in a post-operative orthosis", The International Society for Prosthetics and Orthotics, 2015.

[11] www.maxon.net

[12] J. A. Martinez, Paul Ng, Son Lu, M. S. Campagna and O. Celik, "Design of Wrist Gimbal: a Forearm and Wrist Exoskeleton for Stroke Rehabilitation," 2013 IEEE International Conference on Rehabilitation Robotics, 24-26 June 2013