Chapter 7

A Robot-Assisted Rehabilitation System – RehabRoby

7.1. Introduction

Robot-assisted rehabilitation that can quantitatively monitor and adapt to patient progress and ensure consistency during rehabilitation has become an active research area. Robot-assisted rehabilitation systems have been developed for upper, lower, or both upper and lower extremities.

This chapter presents the development of an upper extremity robot-assisted rehabilitation system called RehabRoby. RehabRoby has been designed in such a way that (1) it can implement passive, active-assisted and resistive-assisted therapy modes, (2) it can be easily adjusted for people with different heights and arm lengths and (3) it can be used for both right and left arm rehabilitation.

Note that the control of RehabRoby in a desired and safe manner is an important issue. Impedance control [KRE 07, ROS 07, NEF 07, FRI 07, KOU 07], admittance control [LUM 06, LOU 03, ROS 07, NEF 07], position control [LUM 06] and force control [SAN 06] have previously been used in the control of the upper extremity robot-assisted rehabilitation systems. There is a human–robot interaction in the robot-assisted rehabilitation systems, which is an external effect that can cause changes in the dynamics of the

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robotic systems. The changes in the dynamics of the robot may result in instability, which may affect the tracking performance. Therefore, a controller that is independent of the dynamic model of robot-assisted system is needed for RehabRoby to compensate changes in the dynamics of the robotic system [TSE 07]. Admittance control with an inner robust position control loop is used to control RehabRoby in a desired manner.

Note that it is also desirable for a patient to perform the rehabilitation task in a safe manner. A high-level controller, which is a decision-making mechanism, is designed to ensure safety during the execution of the rehabilitation task. The high-level controller presented in this chapter plays the role of a human supervisor (therapist) who would otherwise monitor the task and assess whether the rehabilitation task needs to be updated.

In this chapter, background of robot-assisted rehabilitation systems is presented in section 7.2. The control architecture of RehabRoby is given in section 7.3. In section 7.4, design specifications and hardware of RehabRoby are presented. Controllers designed for RehabRoby are described in section 7.5. Conclusion of the chapter and plans for future work are given in section 7.6.

7.2. Background

Rehabilitation robotics has been an active research area since 1985. Robot-supported therapy systems were first used in large-scale clinical tests in 1998, and until today several robot-assisted rehabilitation systems for upper extremities have been developed [KRE 04, TAK 05].

7.2.1. *Robot-assisted rehabilitation systems for upper extremities*

Existing robot-assisted rehabilitation systems for upper extremities either provide a therapy that focuses on multiple joint movements to perform activities of daily living (ADL) tasks or provide a therapy that focuses only on a single joint movement. End-effector-based or exoskeleton-type robots have been previously used to help patients to perform ADL tasks in therapy.

The end-effector-based robot is connected to the patient's limb from one point (hand or forearm). The exoskeleton-type robot is connected to the patient's arm from multiple points to resemble the kinematic structure of the arm. The technical rotation axes and the number of degrees of freedom (DoF) of the robot can be selected arbitarily and independent of the human arm anatomy. Thus, the mechanical design and construction of the end-effector-based robots are much easier [HES 05]. However, exoskeleton-type robots resemble the human arm anatomy, and the technical rotation axes of the robot must correspond to the rotation axis of the human joints [SAN 06]. Thus, the exoskeleton-type robots have a more complex mechanical design compared to end-effector-based robots. Additionally, the arm posture is fully determined, and each joint torque can be controlled separately in exoskeleton-type robots, which reduces control issue complexity, and hyperextensions can be avoided mechanically. MIT-Manus [KRE 07], mirror image movement enabler (MIME) [LUM 06], GENTLE/S [LOU 03] and NeRoBot [ROS 07] are previously developed end-effector-based robot-assisted rehabilitation systems. ARMin [NEF 07], T-WREX [HOU 07], Pneu-WREX [SAN 06], L-Exos [FRI 07] and Salford rehabilitation exoskeleton (SRE) [KOU 07] are existing exoskeleton-type robot-assisted rehabilitation systems.

MIT-Manus provides two-dimensional movements of the patient's hand [KRE 07]. The end-effector of MIT-Manus is the robot-mounted handle gripped by the patient, and forces and movements can be applied to the system using this handle. The MIME robot-assisted system has been developed with the cooperation of Stanford University and Veterans Affairs Palo Alto Health Care System [LUM 06]. Patients can achieve three-dimensional ADL movements during the therapy with MIME system. The MIME mechanism is composed of a PUMA 560, a six-DoF industrial robot manipulator, and a hand attachment in the end-effector. It is possible to execute passive, active and active-limited therapy methods using MIME. GENTLE/s is another end-effector-based robot, which consists of a three-DoF robot manipulator named Haptic Master and a virtual reality (VR) [LUM 06]. GENTLE/s allows patients to perform three-dimensional point-to-point movements. NeReBot has been designed as a three-DoF, wire-driven, end-effector-based robot for upper extremity rehabilitation [ROS 07]. There are three wires, which are connected to the patient's upper limbs through a spline in NeRoBot. The rehabilitation treatment based on the passive or active-assistive spatial motion of the limb is provided controlling the lengths of the wires driven by electric motors.

ARMin, which has been designed for arm therapy is an exoskeleton robot equipped with position and force sensors [NEF 07]. ARMin has four active and two passive DoF to allow elbow flexion/extension and spatial shoulder movements. Later, a second version of ARMin, called ARMin II, has been developed [NEF 07]. The mechanical structure, actuators and sensors of the ARMin have been optimized for the applications of impedance and admittance control for ARMin II. Three therapy modes, which are passive mobilization, game therapy and task-oriented training, can be applied to patients with ARMin II. A new ergonomic shoulder actuation principle and its implementation of ARMin II have been developed, which is called ARMin III [NEF 07]. Three actuated DoF for the shoulder and one for the elbow joint are included in ARMin III. Actuated lower arm pronation/supination and wrist flexion/extension are made available with the additional module in ARMin III. Currently, ARMin III is in use for clinical evaluation in hospitals in Switzerland and the United States. The T-WREX (therapy Wilmington robotic exoskeleton) is a passive, five-DoF and body-powered device with no actuators exoskeleton. T-WREX has been designed to enable patients with significant arm weakness to achieve intense movement training without the expense of a physiotherapist [HOU 07]. It provides a large three-dimensional workspace that is approximately 66% of the natural workspace of the arm in the vertical plane and 72% in the horizontal plane. Weak patients can move their affected arm easily with the support provided against the gravity. Pneu-WREX is a robotic version of T-WREX that can apply a wide range of forces to the arm during upper extremity movements using pneumatic actuators [SAN 06]. L-Exos (light exoskeleton) is an exoskeleton robot with force feedback that has five DoF, four of which are actuated, and it can apply a controllable force up to 100 N at the center of the patient's hand palm [FRI 07]. The results of the clinical trials demonstrate that L-Exos can be used for robotic arm rehabilitation therapy when it is integrated with a VR system. The SRE is a gravity-compensated arm rehabilitation exoskeleton robot with seven DoF [KOU 07]. Three of these DoF are located at the shoulder for flexion/extension, abduction/adduction and lateral/medial rotation. Two are at the elbow for flexion/extension and pronation/supination of the forearm. The other two provide flexion/extension and abduction/adduction located at the wrist. Pneumatic actuation techniques that provide accurate position and force-controlled paths, compliance and a high level of inherent safety are used in the design of the exoskeleton.

7.2.2. *Controllers of robot-assisted rehabilitation systems for upper extremities*

Control of a robot-assisted rehabilitation system is an important issue to complete the rehabilitation task in a desired and safe manner. MIT-Manus uses impedance controller to support the motion of the hand to the target position. MIT-Manus is back-drivable with low inertia and friction [KRE 07].

Thus, it is possible to complete the rehabilitation task in a safe manner during the interaction between the patient and the robot. Force and position sensors are used to feed the impedance controller. Position and admittance control strategies are implemented with the six-DoF force–torque sensor and position sensors in MIME to execute four different control modes (passive, active-assisted, active constrained and bilateral modes) [LUM 06]. GENTLE/s provides assistance to the patients to move to the target points along the predefined trajectories using the admittance control [LOU 03]. Switching proportional-integral-derivative (PID) control has been used for the position control of NeReBot [ROS 07]. Impedance and admittance control techniques have been used for the ARMin robot-assisted rehabilitation systems [NEF 07]. Nonlinear force control and passive counter balancing techniques have been used for Pneu-Wrex [SAN 06]. Impedance control has been used for L-Exos and SRE [FRI 07, KOU 07].

7.3. Control architecture

A control architecture, which is composed of hardware and software components to complete the rehabilitation tasks in a desired and safe manner, has been developed for robot-assisted rehabilitation system RehabRoby [ÖZK 11a, ÖZK 11b, ÖZK 11c, ÖZK 12]. The control architecture consists of the rehabilitation robot (RehabRoby), low-level and high-level controllers, and a sensory information module. The block diagram of the control architecture is illustrated in Figure 7.1.

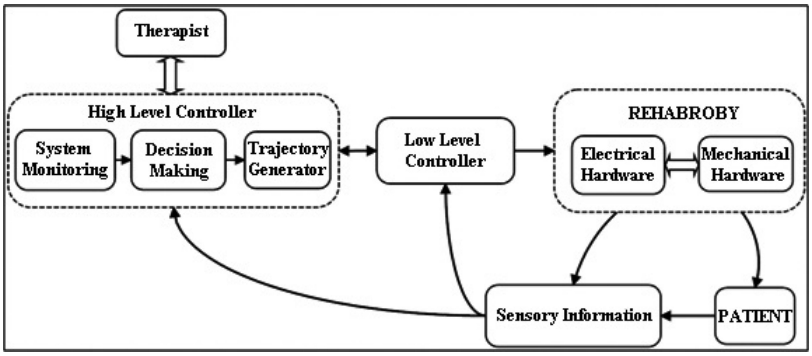

Figure 7.1. *Control architecture of RehabRoby*

7.4. RehabRoby

Upper extremity movement characteristics of a human are evaluated during the design phase of RehabRoby. Orthopedic society has provided a standard terminology, which is based on a consensus on three items, to describe upper extremity movements and movement limits for common clinical examination [LIV 65]. First, all positions are referenced on the anatomical posture defined as zero positions of the joint. Second, joint positions are measured in one of the three (orthogonal) planes (sagittal, frontal or transversal) or around the longitudinal axis (rotation). Finally, the degrees of motion are recorded as the deviation from the reference position in either direction from the anatomical position in a standardized format.

RehabRoby has been designed to provide basic upper extremity rehabilitation movements (extension, flexion, abduction, adduction, rotation, pronation and supination) and also a combination of these movements that are necessary for ADL. RehabRoby's motion axes are given in Figure 7.2. The range of motion (ROM), joint torques, velocities and accelerations for RehabRoby have been determined using the measurements of the movements of a healthy subject during two ADL tasks [FAS 04, OLD 07]. Higher joint torque values given in [FAS 04] and [OLD 07] have been selected to assure that RehabRoby is strong enough to overcome resistance from the human against movements due to spasms and other complications that are difficult to model. These joint torque values are used to select the proper combination of motors and gear units for each joint of RehabRoby. Motion specifications of RehabRoby are given in Table 7.1.

Axis	ROM (deg)	Maximum Torque (Nm)	Maximum Velocity (deg/s)
θ_1	–135° to 45°	34.9	332.28
θ_2	–135° to 45°	23.35	447.6
θ_3	−90° to 90°	90.44	78.16
θ_4	−90° to 30°	34.9	332.28
θ_5	−90° to 90°	53.4	72.44
θ_6	−50° to 79°	8.5	483

Table 7.1. *Motion specifications of RehabRoby*

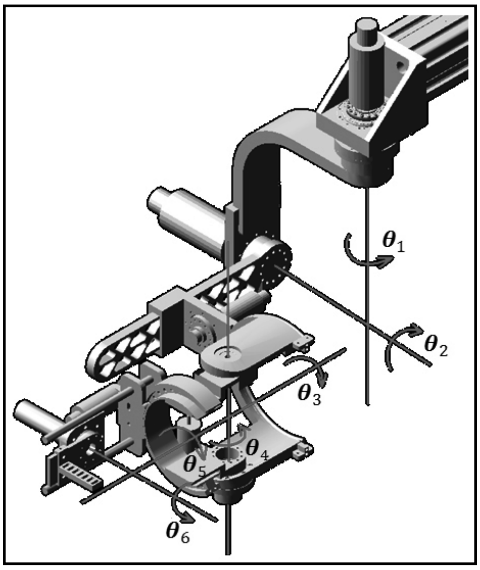

Figure 7.2. *RehabRoby's axes (θ_1: horizontal abduction/adduction of shoulder rotation, θ_2: shoulder flexion/extension elevation, θ_3: internal and external rotation of shoulder, θ_4: elbow flexion/extension, θ_5: lower arm elbow pronation/supination and θ_6: wrist flexion/extension)*

Maxon's brushed DC motors, EPOS model drivers (Maxon Motor AG, Switzerland) and gear units of Harmonic Drive (Harmonic Drive Inc., Japan) have been selected for the actuation of the joints of RehabRoby. There is a coupling between flexion/extension and abduction/adduction of shoulder axis. The position of the horizontal shoulder rotation angle, which is defined as θ_1 in Figure 7.2, determines the separation of the shoulder movements. When θ_1 is 0°, θ_2, which represents the position of the flexion/extension and abduction/adduction of shoulder axis as shown in Figure 7.2, is responsible for the flexion/extension of shoulder. When θ_1 is 90°, θ_2 is responsible for the abduction/adduction of shoulder.

An arm splint is designed and attached to RehabRoby as shown in Figure 7.3. It has humeral and forearm thermoplastic supports with Velcro straps and a single axis free elbow joint. A thermoplastic inner layer covered by soft material (plastazote) is used due to the differences in the size of the subjects' arms. Thus, the total contact between the arm and the splint can be achieved to eliminate the loss of movement during the execution of the task.

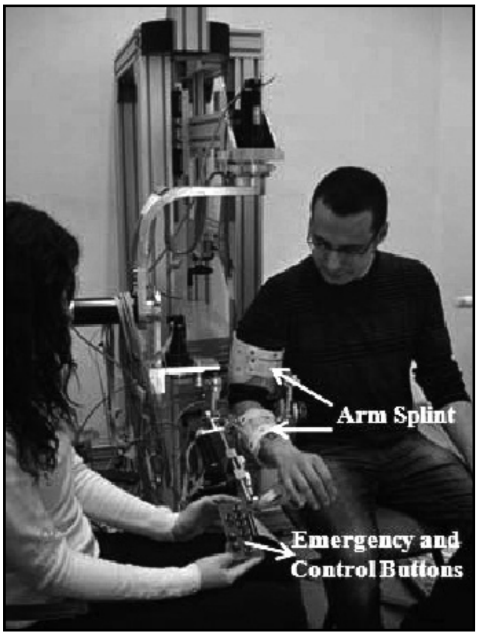

Figure 7.3. *The RehabRoby system with arm splint and emergency buttons*

Ensuring safety of the subject is an important issue when designing a robot-assisted rehabilitation system. Thus, in case of emergency situations, the physiotherapist can press an emergency stop button to stop the RehabRoby (Figure 7.3). The motor drivers of RehabRoby can be disabled separately or together by pressing enable/disable buttons without disconnecting the energy of the RehabRoby. The power of the system is supported by an uninterruptible power supply. Thus, there is no power loss, and RehabRoby will not collapse at any time. Additionally, the rotation angle and angular velocity of each joint of RehabRoby are monitored by the high-level controller described in section 7.5.

RehabRoby has been designed in such a way that it can be easily adjustable for people of different heights and arm lengths. Anthropometric approaches have been used in the design of RehabRoby. The link lengths of RehabRoby are based on the arm lengths of 2,100 people in 14 cities in Turkey [GUL 07]. The adjustable link lengths and height of RehabRoby are shown in Figure 7.4. L_1, which is the adjustable upper arm length value, varies from 260 to 400 mm. L_2, which is the adjustable lower arm length value, varies from 200 to 300 mm. Additionally, RehabRoby's height (L_3) can be adjusted for each subject using a screw shaft mechanism that can be manually operated using a wheel.

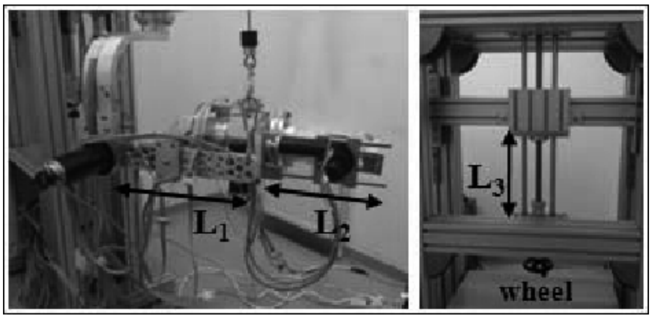

Figure 7.4. *Adjustable link lengths and height of RehabRoby*

RehabRoby is integrated with a counterweight mechanism as illustrated in Figure 7.5 to reduce the effect of gravity to help subjects to flex their shoulders easily. Note that the counterweight system is designed in such a way that it does not interfere with the subject's workspace.

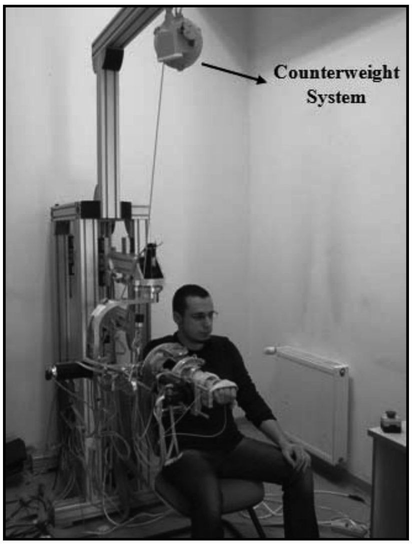

Figure 7.5. *RehabRoby with a counterweight system*

RehabRoby can be used for both right and left arm rehabilitation. It can be translated from right arm use to left arm use with the following steps: (1) RehabRoby is rotated 90° about θ_2; (2) then, it is rotated 180° about θ_1; and (3) finally, it is rotated -90° about θ_2.

RehabRoby has an interface with Matlab® Simulink/Realtime Workshop to allow fast and easy system development. Humusoft Mf624 model (Humusoft Inc., Czech Republic) data acquisition board is selected to provide real-time communication between the computer and other electrical hardware. Humusoft Mf624 data acquisition board is compatible with Real-Time Windows Target toolbox of Matlab®/Simulink. Digital incremental quadrature encoders are coupled with brushed DC motors for joint position measurement. Five of the six encoders have resolutions of 500 counts/turn, and one of them has a resolution of 1,000 counts/turn. Kistler's press force sensors (Kistler Holding AG, Winterthur, Switzerland), which are quite small in size, are selected to measure contact forces between the subject and RehabRoby. Two force sensors are placed in the inner surface of the thermoplastic molded plate attached dorsally to the forearm splint via Velcro straps in such a way that their measurement axes are perpendicular to each other. The placement of the force sensors is illustrated in Figure 7.6. One of the force sensors is used to measure the applied force during the elbow flexion movement. The other one measures the applied force during the shoulder flexion movement. Digital encoder data of motors and analog force data from the force sensors are received through the data acquisition board with a sampling frequency of 500 Hz.

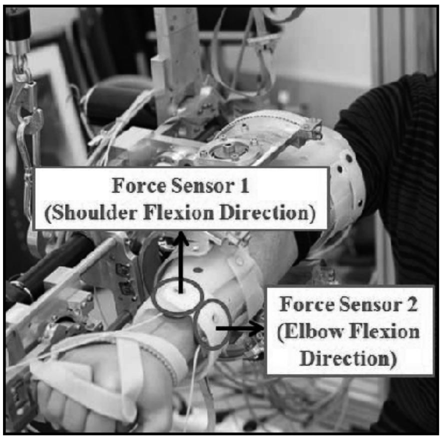

Figure 7.6. *Placement of the force sensors*

The closed-loop data flow in the control hardware occurs between the computer, data acquisition board, microcontroller circuits, motor drivers and motors with encoders. The control inputs, which are the current reference values of the motors of RehabRoby, are transmitted to the microcontroller circuits through analog outputs of the data acquisition board Humusoft Mf624 with a sampling frequency of 500 Hz. The incoming analog data are converted into digital data and transmitted to the motor drivers using RS232 serial bus with a baud rate of 115,200 by programmable interface controller (PIC) microcontrollers (Microchip Technology Inc., AZ, USA) in the microcontroller circuits. Here, microcontroller circuits are used because four of the six motor drivers of RehabRoby have no analog reference inputs. Analog to digital conversion and serial transmission are completed within 2 ms. Motor drivers send the reference current values to the motors using a simple current control algorithm to equalize the current values of the motors with the reference ones. Angular changes in the axes are measured by digital encoders coupled with the motors of RehabRoby and transmitted to the Matlab®/Simulink model in the computer as feedback through encoder inputs of the data acquisition board Humusoft Mf624. The block diagram of the general data flow in the hardware is shown in Figure 7.7.

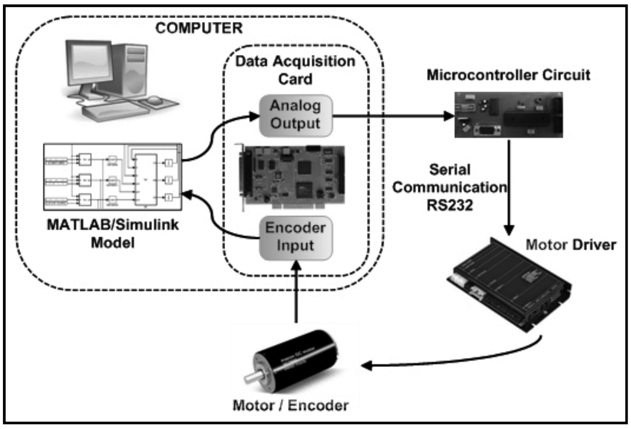

Figure 7.7. *General data flow in the control hardware*

7.5. Controllers of RehabRoby

The control structure of RehabRoby consists of low-level and high-level controllers. Admittance control with inner robust position control loop is used to control RehabRoby to provide assistance to the patients. The position control of the joints of RehabRoby is provided by a robust controller with a Kalman filter-based disturbance estimator to minimize the effects of the uncertainties in the dynamics of RehabRoby because of its complex structure [STA 99]. The interaction forces between the subjects and RehabRoby are controlled using the admittance control technique. Additionally, a high-level controller is designed as a decision-making mechanism of RehabRoby using hybrid system modeling technique to monitor the task and assess whether the rehabilitation task or any parameter in the low-level controller needs to be updated.

7.5.1. *Low-level controller*

The low-level controller is responsible for providing necessary motion to RehabRoby. Therefore, patients can complete the rehabilitation tasks in a desired manner. An admittance control with an inner robust position control loop is used as the low-level controller of RehabRoby.

The admittance control method, which has low back drivability, high inertia and reliable position and force/torque information, is a good choice for control applications of the robotic systems [NEF 07]. Moreover, the position and torque sensors of RehabRoby have high resolutions, so admittance control could be a good choice. Because RehabRoby has complex and uncertain inner dynamics and it is sensitive to external forces during the human–robot interaction, a simple PID or model-based position control technique may not be enough. Hence, a robust position controller is used in the inner loop of the admittance controller. The effects of the parametric uncertainties in the dynamic model and the external additive disturbances are compensated with an equivalent disturbance estimator in the robust position controller. Various methods have been previously used to estimate the disturbance in the position control of robotic systems such as an adaptive hierarchical fuzzy algorithm and a model-based disturbance attenuation [EMA 04, CHO 03]. A discrete Kalman filter-based disturbance estimator [STA 99, JUN 98], which is a well-known technique for processing noisy discrete measurements and high-accuracy estimation of the unknown states and parameters, is used in this study. To our knowledge, admittance control with inner robust position control loop has not been used to control robot-assisted rehabilitation systems before.

The general structure of the proposed low-level controller for RehabRoby is given in Figure 7.8. The force that is applied by the subject during the execution of the task is measured using the force sensor, and this value is then converted to torque using Jacobian matrix. The torque value is then passed through an admittance filter, which is used to define characteristics of the motion of the RehabRoby against the applied forces, to generate the reference motion for the robust position controller [JUN 98]. The reference motion is then tracked with a robust position control that consists of a linear Kalman filter-based disturbance estimator [STA 99, SAL 95].

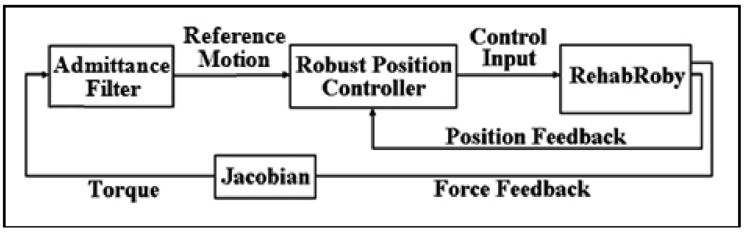

Figure 7.8. *Block diagram of the low-level controller of RehabRoby*

7.5.2. *High-level controller*

The high-level controller is the decision-making mechanism of RehabRoby. It decides necessary changes by analyzing information that comes from the sensory information module or the therapist. The high-level controller plays the role of a human supervisor (therapist) who would otherwise monitor the task and assess whether the task needs to be updated. A hybrid system modeling technique is used to design the high-level controller because it is easy to add new rules related to a rehabilitation task using this technique.

The block diagram of a high-level controller is illustrated in Figure 7.9. Initially, the states of the high-level controller are defined. When task execution commences, the starting and final positions of the joint angles of RehabRoby are initialized in the initialization state. Passive state (mode = 0) (passive mode), active state (mode = 1) (active-assisted mode) or admittance control state (mode = 2) (resistive-assisted mode) become active based on the mode selected by the therapist. The rehabilitation task is performed only in the passive state in which RehabRoby is responsible to help the subject complete the task when he/she is passive in the passive mode. The subject's motion is checked periodically in the active-assisted and resistive-assisted modes. If the subject's movement, which is measured as (θ) of RehabRoby, is out of limits ($\theta \geq |\varepsilon|$), then the position control state becomes active. When the position control state is active, the RehabRoby provides assistance to the subject's motion until the subject's movement is in the desired motion range. When the subject's movement is in the range of limits ($\theta < |\varepsilon|$), the state that is active before entering the position control state becomes active again. In any state, safety conditions of RehabRoby are checked periodically, and if any unsafe situation occurs ($e = 1$), then the emergency stop state becomes active, and the execution of the task stops.

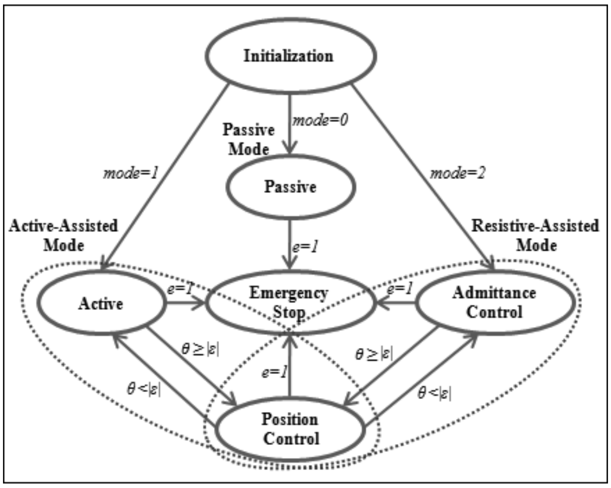

Figure 7.9. *Block diagram of the high-level controller of RehabRoby*

7.6. Concluding remarks

An exoskeleton-type upper extremity robot-assisted rehabilitation system, called RehabRoby, has been developed. RehabRoby is adaptable for patients of both genders, is adjustable for people with different arm lengths, and is usable for both right and left arms.

A control architecture which consists of a high-level controller and a low-level controller has been developed for RehabRoby. Low-level controllers can provide the necessary motion to RehabRoby to perform the rehabilitation tasks in a desired manner. Admittance control with inner robust position control loop, which provides the necessary motion to RehabRoby to complete the rehabilitation task in a desired manner, is used. The level of resistance applied by RehabRoby can be varied using admittance control based on the patient's movement capability. Admittance controller has been integrated with a robust position controller which consists of a linear discrete Kalman filter to compensate effects of the parameter variations, and nonlinearities in the inherent dynamic model of RehabRoby and the external forces that may affect the human–robot interaction. When the disturbances are compensated, it becomes possible to control the position of RehabRoby with feedforward and state feedback techniques using a robust position controller. Furthermore, an admittance control with an inner robust position control loop does not need an exact knowledge of RehabRoby's dynamic model; thus, the computation effort of the control algorithm is minimized. The high-level controller is the decision-making mechanism that decides the necessary changes in the low-level controller according to the sensory information or the therapist's commands. A hybrid system modeling technique has been used for the high-level controller, which provides flexibility in interfacing the low-level controller without extensive redesign cost.

RehabRoby can provide passive, active-assisted and resistive-assisted therapy modes; thus, it is possible for low-functioning and high-functioning patients to use RehabRoby in their rehabilitation programs. The transitions between the controllers (when needed) can be completed in a smooth manner without causing any nonlinearities and jerks with the high-level controller, which is an important issue during execution of the rehabilitation tasks.

As future research, the robust position controller of RehabRoby can be improved using an adaptive Kalman filter. The capability of RehabRoby can be extended adding new therapy modes. Additionally, the proposed robot-assisted rehabilitation system RehabRoby will be used in the future for the rehabilitation of stroke patients.

7.7. Acknowledgments

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