An upper limb rehabilitative robot with ergonomic shoulder to provide patient tailored therapy

Md Rasedul Islam, Md Assad-Uz-Zaman, Asif Al Zubayer Swapnil, Mohammad Habibur rahman

Bio-Robotics Lab, Department of Mechanical Engineering, College of Engineering and Applied Science

Abstract

The robotic intervention in upper limb rehabilitation of post-stroke patients has gained traction nowadays. However, existing devices have some limitations in hardware and control approach. To provide task-specific and patient-tailored therapy to individuals with upper limb impairment, those limitation should be addressed. At UWM's Bio-Robotics lab, we have built an upper limb rehabilitative robot, namely, u-Rob that overcome three such key limitations (i.e. Mobility of Shoulder joint' center of rotation, being able to provide both end-point exercise and individual joint exercises and being able to provide limb-segment tailored therapy). The experiments with healthy subject have proved its intended functionality. The trajectory-tracking of the developed u-Rob shows an excellent control during maneuvering with tracking error less than unity.

Challenges:

Being able to do exercise repetitively and precisely, robotic devices have been quite popular these days. That being said, there need to address some challenges to provide quality, safe and effective rehabilitation. Existing literature mentioned following three key limitations which need to be overcome [1-2].

1. Mobility of the shoulder joint's center for full natural range of motion.
2. Existing devices are either end-effector type (suitable for end-point exercises) or exoskeleton type (suitable for individual joint exercises).
3. Patient-tailored therapy.

Methodology:

To address above mentioned challenges,

1. Shoulder joint does not remain fixed during its movement. To provide shoulder joint's mobility without trading off with ROM, we have designed two passively actuated parallel mechanisms that realize movement of shoulder joint during shoulder abduction-adduction and flexion-extension as shown in figure. The mechanism was analyzed in MATLAB and ADAMS to see its intended functionality.

2. To provide patient-tailored therapy, we have developed a robot, namely, u-Rob, to provide end point exercises (end-effector type) and individual joint movement exercises (exoskeleton type) as shown in figure. For exoskeleton type setup, joint-based control approach was applied while for end-effector type setup, cartesian based control was employed using inverse kinematic solution.

3. To make the exoskeleton's structure tailored for patients, u-Rob designed in a way to attach/detach its motion support part to reconfigure its kinematic structure. Besides, corresponding control approach for every configuration was employed

Workspace and DH parameter

- Based on the available literature[3-4], following range of motions are selected for u-ROB as presented in table-1.
- The modified DH parameter [5] was computed in table-2 according to coordinate frame assignment as shown in fig 2(b).

Contact Information

Bio-Robotics Lab, USRB 281
Mechanical Engineering Department, UWM

Md Rasedul Islam, PhD Candidate, islam4@uwm.edu
Dr. Mohammad Habibur Rahman, Research Advisor, rahmanmh@uwm.edu

Table-1: Range of Motion of u-Rob

Limb Segment	Joint No	Kinds of Motion	Range of Motion
Shoulder	Joint-1	Abduction	180°
		Adduction	0°
	Joint-2	Vertical flexion	180°
		Vertical extension	0°
	Joint-3	Internal rotation	90°
		External rotation	90°
Elbow and Forearm	Joint-4	Flexion	145°
		Extension	0°
	Joint-5	Pronation	90°
		Supination	90°
Wrist	Joint-6	Radial deviation	20°
		Ulnar deviation	30°
	Joint-7	Flexion	60°
		Extension	50°

Table-2: Computed Modifed DH parameter

Joint (i)	α_{i-1} (Link twist)	a_{i-1} (Link length)	d_i (Link offset)	q_i (Joint variable)
1	0	0	L_0	q_1
2	$\pi/2$	0	0	$q_2 + \pi/2$
3	$\pi/2$	0	L_2	q_3
4	$-\pi/2$	0	0	q_4
5	$\pi/2$	0	L_4	q_5
6	$-\pi/2$	0	0	$q_6 - \pi/2$
7	$-\pi/2$	0	0	q_7

Shoulder Mechanisms

The parallel mechanism for realizing shoulder joint movement are shown in fig. 1 and fig 2(a). As shown in fig.1(b), shoulder joint instantaneous center follows a circular arc by constraining motion from link1B as it is hinged at its left end. Other mechanism as shown in fig 2(a) works in similar fashion too.

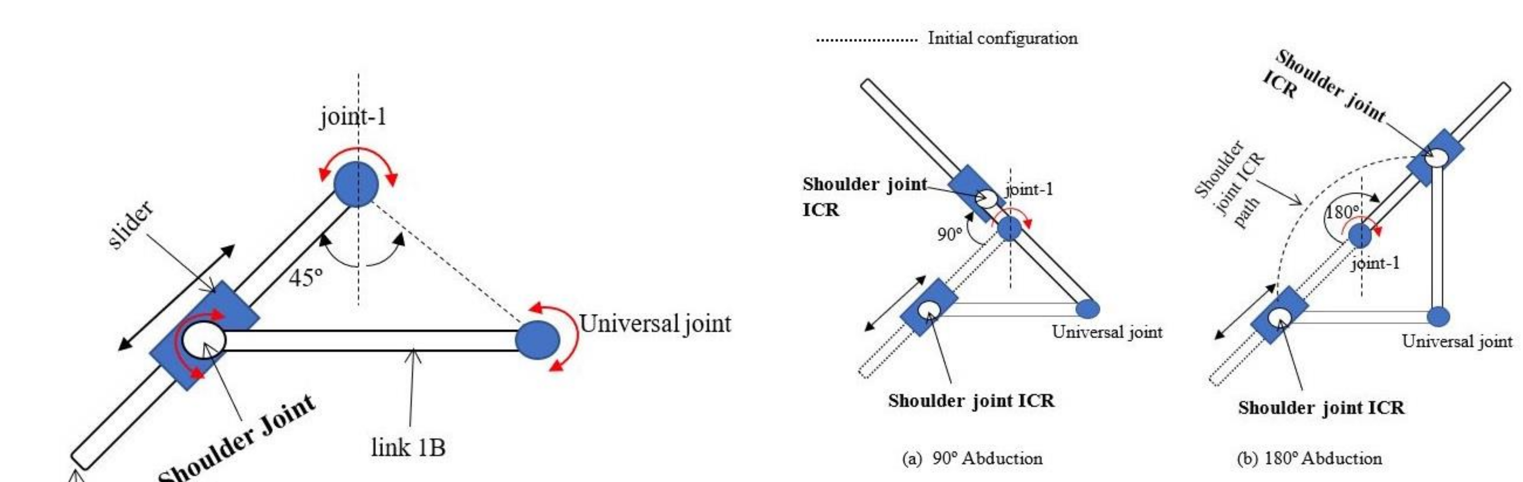

Figure 1: mechanism for Abduction-adduction (left) and corresponding location of shoulder joint CR (Right)

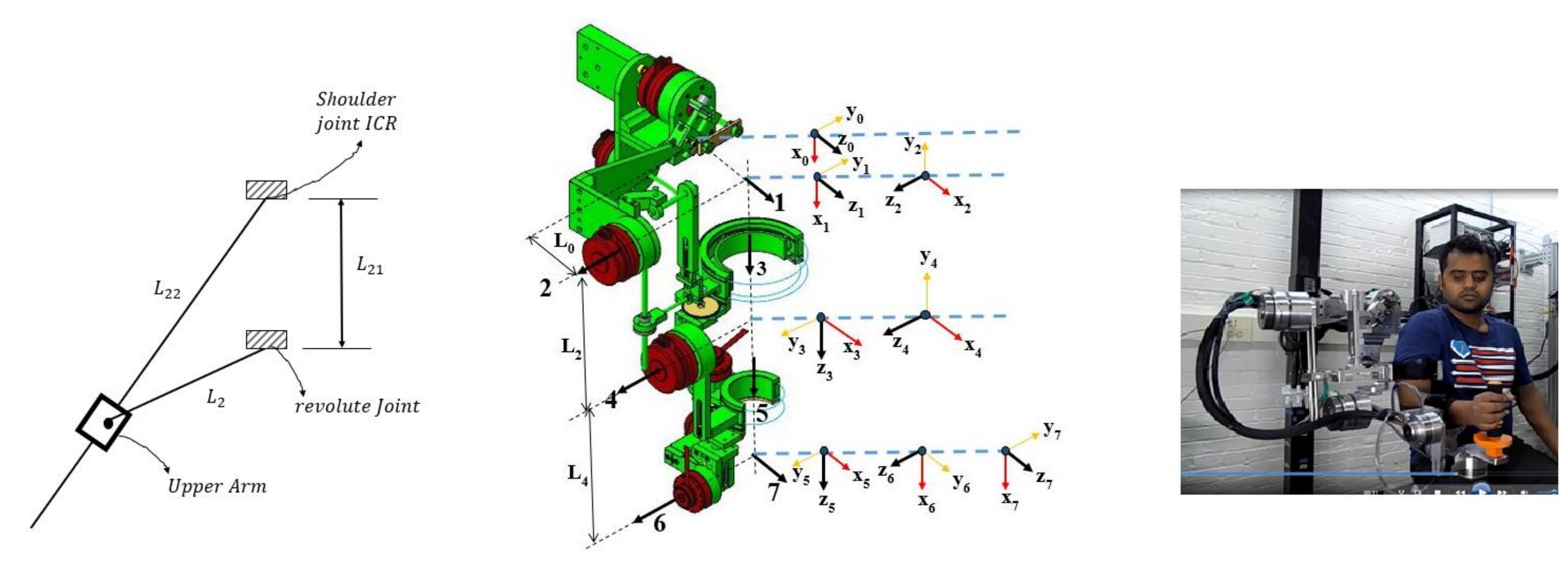

Figure 2: Mechanism for shoulder vertical flexion/extension, Coordinate frame assignment and subject wearing u-rob

Dynamic Model

The dynamic model of the u-Rob was derived using Newton-Euler formulation [5].

$$\tau = M(q)\ddot{q} + V(q,\dot{q}) + G(q) + F(q,\dot{q})$$

Where $M(q)$ is the 7× 7 mass matrix of the manipulator, $V(q,\dot{q})$ is a 7× 1 dimension vector composed of centrifugal and Coriolis terms, and $G(q)$ is a 7× 1 vector of gravity terms. In addition, $F(q,\dot{q})$ is a 7× 1 vector of nonlinear coulomb friction. Modified Parameter was used to compute dynamics of u-Rob.

Control

Since anthropometric parameter (arm length, arm segment's weight, segment inertia) vary patient to patient, a hybrid controller, as given below, based on robot model and tracking error were used in u-Rob to do rehabilitative exercises. The Lyapunov stability of control law was derived.

$$\tau = -K_p e - K_v \dot{e} + M\ddot{q}_d + C\dot{q}_d + G + F$$

Where, K_p *and* K_v *are positive definite diagonal gain matrix*, and $\ddot{q}_d$ is the desires acceleration.

Experiments and Results

- The GUI was developed in NI LabVIEW to communicate with u-Rob as a remote target.
- In the developed u-Rob, rehab exercises were given in the form of joint trajectory (position, velocity and acceleration). The u-Rob while carrying patients limb then followed the given. Experiments were conducted with 5 healthy subjects.
- The experiments were done for end-point exercises and individual joint exercises. Besides, experiment was also done for only shoulder module (by removing elbow and wrist motion support parts). The following results as shown in fig.5 are shown for shoulder full natural ROM as shown in fig.3. Note that, this is an exoskeleton setup of u-Rob.

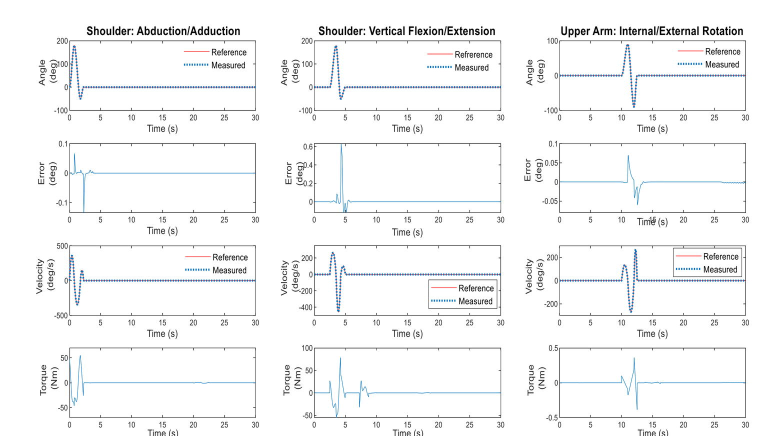

Figure 5: Trajectory tracking of exercises shown in Fig 3

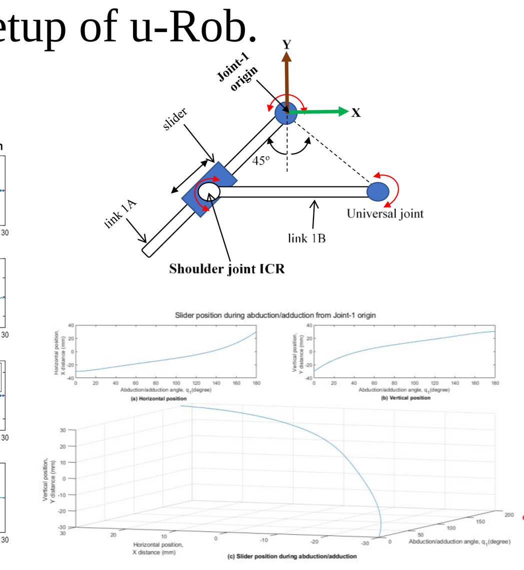

Figure 4: Shoulder joint CR position during joint-1 movement

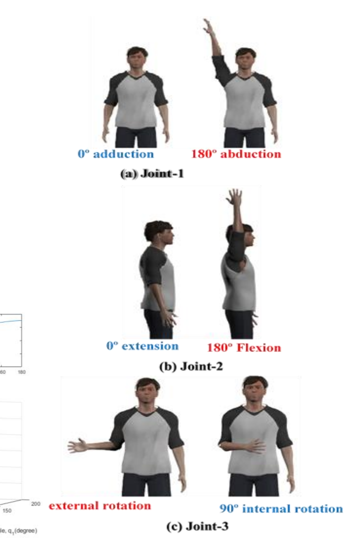

Figure 3: Schematic of shoulder joint full ROM exercises

To do the end-point exercises, a planar movement (circular trajectory) was experimented. The control schematic for this particular exercises is shown in fig.6. The position tracking of end-effector is shown in fig. 7.

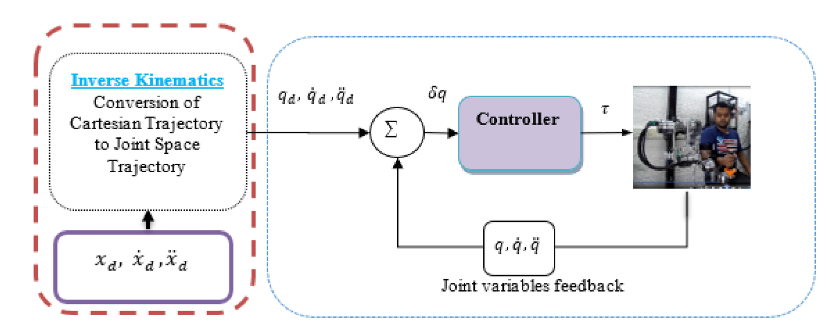

Figure 6: Schematic diagram of cartesian control setup

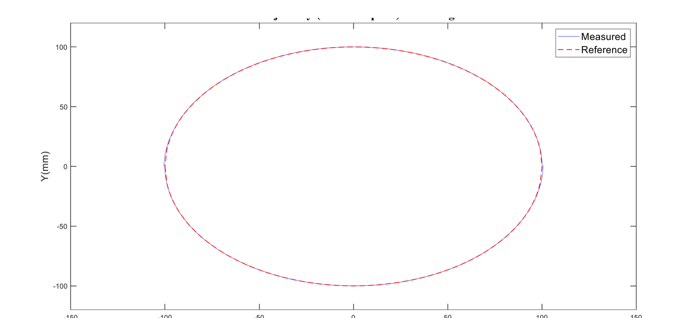

Figure 7: Cartesian trajectory tracking with u-Rob

Result Discussion

Figure 5 shows the plot for joint position (both desired and measured), error and torque whereas Figure 7 presents position of end-effector.

- As shown in fig.5 shows controller is stable and u-Rob is able to do full ROM exercises.
- Figure 4 shows shoulder joint CR moves during shoulder movement exercises.
- Figure 7 shows u-Rob doing end-point exercises. So u-Rob can function as both end-effector type and exoskeleton type.
- Besides, u-Rob was reconfigured by removing its elbow and wrist module, which shows u-Rob's ability to offer patient tailored therapy

References

1. Maciejasz, P., Eschweiler, J., Gerlach-hahn, K., Jansen-troy, A. & Leonhardt, S. 2014. A survey on robotic devices for upper limb rehabilitation. Journal of NeuroEngineering and Rehabilitation, 11, 3.
2. Islam, M., Spiewak, C., Rahman, M. & Fareh, R. 2017. A Brief Review on Robotic Exoskeletons for Upper Extremity Rehabilitation to Find the Gap between Research Porotype and Commercial Type. Advances in Robot Automation, 6.
3. Van Cott, H. P. & Kinkade, R. G. 1972. Human engineering guide to equipment design, [Washington], [Dept. of Defense; for sale by the Supt. of Docs., U.S. Govt. Print. Off.].
4. Winter, D. A. 2009. Anthropometry. Biomechanics and Motor Control of Human Movement. New York: John Wiley & Sons.
5. Craig, John J. Introduction to Robotics: Mechanics and Control. Noida, India: Dorling Kindersley (India) Pvt. Ltd, 2009. Print.