# Development of a Vision-Based Motion Imitation System to Provide Mirror Therapy with a Wearable Upper Extremity Robotic Exoskeleton

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## Abstract

In this research, we present a robot-assisted human upper limb rehabilitation system that facilitates the concept of mirror therapy. The system, designed for people with impaired upper extremity, uses his/her functional arm or the functional arm of any other person as a medium to generate therapeutic exercise for the impaired limb. Here, we intend to capture the motion trajectories of human arm joints while performing rehabilitation exercises or daily activities with a functional upper extremity using marker-less vision sensor Kinect. Afterward, these captured trajectories are fed to a new 7-DOF wearable robotic exoskeleton named UWM-SREx, which imitates the same motion when worn by the people with upper extremity impairment. This allows the participant to use his/her functional limb to generate the desired trajectory, which enables the mirror therapy. Such mirror-symmetric movement promotes the functional recovery of the affected arm, as well as reorganize the motor cortex networks which increase neuroplasticity. Potentially such an approach can generate more complex and realistic motion trajectories compared to conventional methods. In the developed system, motions are captured for the shoulder (vertical and horizontal flexion/extension and internal/external rotation) and elbow (flexion/extension) joint, which provide trajectories for 4-joints of the UWM-SREx. A PID controller has been implemented to track the provided joints trajectories by the exoskeleton robot.

## Introduction

In recent decades, the development of robot-assisted rehabilitation devices and different therapeutic strategies have been increasing tremendously to enhance recovery of people with upper extremity dysfunction. The movement of such devices usually follow pre-defined trajectories generated from the mathematical models. However, it is difficult to describe the complex and realistic trajectories, such as trajectories for daily activities, by mathematical models. Studies indicate that stroke is one of the major causes of disabilities whereas 80% of stroke survivors suffer from one-sided impairment[1]. Hence, realistic trajectories can be generated by capturing the movement of the healthy side[2]. Rehabilitation therapy based on such an approach facilitates a symmetrical position control for both upper extremities and is called mirror therapy or self-motion control. Literature reveals the effectiveness of mirror therapy in rehabilitation[3]. In this research, we proposed a system that tracks human left arm joint coordinates using Kinect sensor to generate motion trajectories for four joints of UWM-SREx. The kinect motion tracking sensor system is a marker-less system and does not require any sophisticated calibration. Thus, it provides a non-intrusive, convenient to use, and inexpensive real-time motion tracking capabilities. UWM-SREx is our recently developed 7-DOF wearable exoskeleton robot that provides rehabilitation therapy to people with upper extremity disabilities. It is designed to be worn on the lateral side of the right upper extremity to provide naturalistic movements of the shoulder (vertical and horizontal flexion/extension and internal/external rotation), elbow (flexion/extension), forearm (pronation/supination), and wrist joint (radial/ulnar deviation and flexion/extension).

## System Architecture

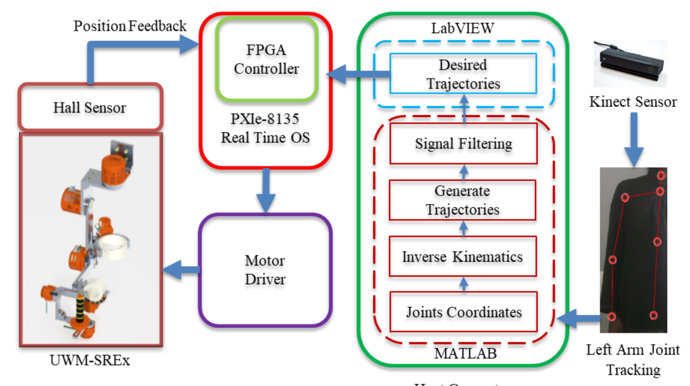
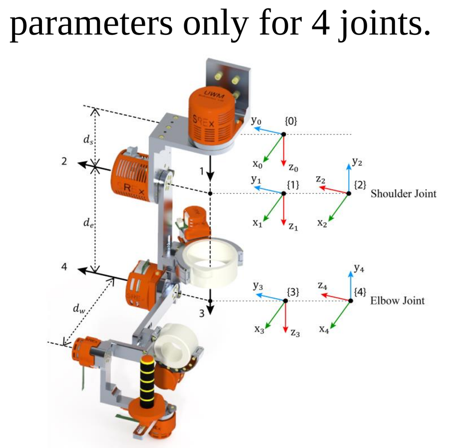



*Fig. 1. The architecture of the proposed system*

## Kinematical Model

For Kinematic modeling of UWM-SREx, modified Denavit-Hartenberg (DH) method has been used. As the proposed system only control first 4 joints of the robot, here we present kinematic parameters only for 4 joints.




| Joint (i) | $\alpha_{i-1}$ | $d_i$ | $a_{i-1}$ | $\theta_i$ |
|---|---|---|---|---|
| 1 | 0 | $d_s$ | 0 | $\theta_1$ |
| 2 | -π/2 | 0 | 0 | $\theta_2$ |
| 3 | π/2 | $d_e$ | 0 | $\theta_3$ |
| 4 | -π/2 | 0 | 0 | $\theta_4$ |
| 5 | 0 | $d_w$ | 0 | 0 |

*Fig. 2. Link frame attachments and Modified DH parameters*

To ensure the proper mapping of joint trajectories form left arm to right handed robot, we consider the left arm kinematic model as the mirror reflection of the robot.

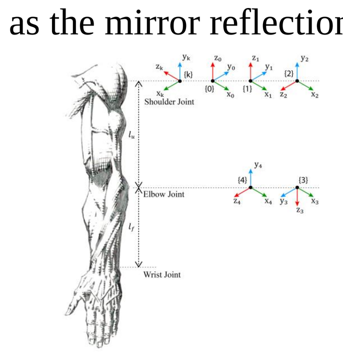



*Fig. 3. Left arm Link frame attachments*

*Table 1. Workspace of UWM-SREx*

| Joint | Motion | Range |
|---|---|---|
| 1 | Shoulder joint horizontal flexion / extension ($\theta_1$) | 0° / 140° |
| 2 | Shoulder joint vertical flexion / extension ($\theta_2$) | 140° / 0° |
| 3 | Shoulder joint internal/external rotation ($\theta_3$) | -90° / +90° |
| 4 | Elbow joint flexion / extension ($\theta_4$) | 145° / 0° |

## Geometric Calculation of Joint Angles

From the Kinect we received the the joint coordinate for shoulder joint $(x_{ks}, y_{ks}, z_{ks})$, elbow joint$(x_{ke}, y_{ke}, z_{ke})$ and wrist joint $(x_{kw}, y_{kw}, z_{kw})$ with respect to coordinate frame {k} in Fig. 3. For simplicity we change the origin to frame {0} by multiplying these coordinates with rotational matrix $R_z(\theta_z)$ ($\theta_z$ = -90°rotation about $z_k$ axis ) and $R_x(\theta_x)$ ($\theta_x$ = 90° rotation about $x_k$ axis ). Hence, we obtain the joint coordinate for shoulder joint O$(x_s, y_s, z_s)$, elbow joint P$(x_e, y_e, z_e)$ and wrist joint Q$(x_w, y_w, z_w)$ with respect to coordinate frame {0} at any instant as shown in Fig. 4. Where, rotational matrix, $R = R_z R_x$

$$R_z = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_z & -\sin\theta_z \\ 0 & \sin\theta_z & \cos\theta_z \end{bmatrix}$$

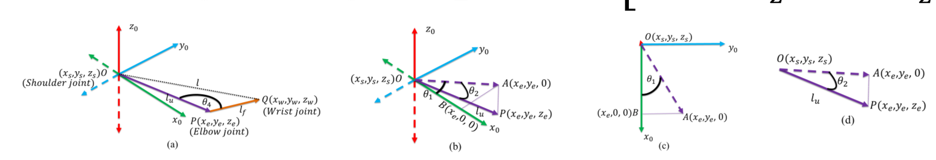



*Fig. 4 Geometrically joint angle $\theta_1$, $\theta_2$, and $\theta_4$ calculation.*

To be consistence with left arm kinematic model (Fig. 3), joint $\theta_1$ move first then joint $\theta_2$. Geometrically it is shown in Fig. 4 (b). One the other hand joint angle $\theta_4$ simply the angle generated by the upper arm ($l_u$) and forearm ($l_f$) vector. Then by cosine we obtain all these three angle as,

$$\cos\theta_1 = \frac{OA^2 + OB^2 - AB^2}{2 \cdot OA \cdot OB}; \quad \cos\theta_2 = \frac{OA^2 + OP^2 - AP^2}{2 \cdot OA \cdot OP}$$

$$\text{and}, \cos\theta_4 = \frac{OP^2 + PQ^2 - OQ^2}{2 \cdot OP \cdot PQ}$$

Finally for $\theta_3$, move back elbow joint to its initial position by multiplying current coordinate with rotational matrix $R_z(-\theta_1)$ ($-\theta_1$ rotation about $z_0$ axis ) and $R_y(-\theta_2)$ ($-\theta_2$ rotation about $y_0$ axis ). Hence, new position of elbow and wrist defined by $P^\star$ and $Q^\star$ as shown in Fig. 5. Where, rotational matrix, $R = R_z R_y$

$$R_z = \begin{bmatrix} \cos(\theta_1) & \sin\theta_1 & 0 \\ -\sin(\theta_1) & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad R_y = \begin{bmatrix} \cos\theta_2 & 0 & -\sin\theta_2 \\ 0 & 1 & 0 \\ \sin\theta_2 & 0 & \cos\theta_2 \end{bmatrix}$$

Now the angle between $z_0 x_0$ plane and $P^\star Q^\star$ vector define the angle $\theta_3$ and obtained buy the following equation,

$$\sin\theta_3 = \frac{(y_w^* - y_e^*)}{\sqrt{(x_w^* - x_e^*)^2 + (y_w^* - y_e^*)^2 + (z_w^* - z_e^*)^2}}$$

To align UWM-SREx joints axes of rotation with that of the human left arm. So, for the trajectory generation joint angles are modified as if $x_e < 0$ then $\theta_{1,robot} = 180° - \theta_1$ otherwise $\theta_{1,robot} = \theta_1$ . If $z_e > 0$ then $\theta_{2,robot} = 180° - \theta_2$ otherwise $\theta_{2,robot} = 90° - \theta_2$ . Finally $\theta_{4,robot} = 180° - \theta_4$ and $\theta_{3,robot} = \theta_3$ .

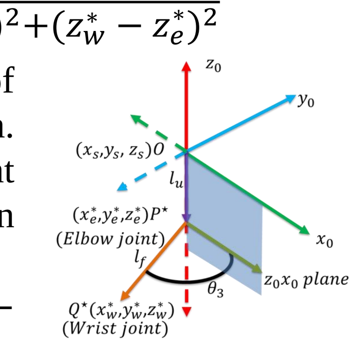



*Fig. 5 Joint angle $\theta_3$ calculation.*

For the convenience of representation, four joint angles of UWM-SREx represented as $\theta_1$, $\theta_2$, $\theta_3$ and $\theta_4$ throughout this paper.

## Signal Smoothing

Kinect sensor has three different source of noise namely spatial noise, temporal noise, and interference noise [4]. Noise level is increased especially for joints that are occluded by other parts of the body. For signa smoothing, we use second order filter given by the equation,

$$\frac{\theta_f}{\theta} = \frac{\omega_o^2}{S^2 + 2\zeta\omega_o S + \omega_o^2}$$

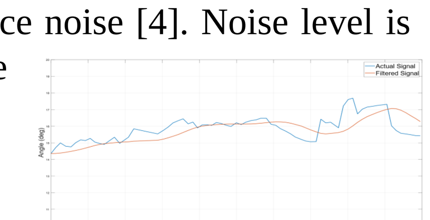


*Fig. 6. Actual and filtered signal from Kinect sensor.*

Here, $\theta$ is the actual angle obtained from the Kinect data, $\theta_f$ is the filter output and S is Laplace operator . The parameters of the filter were set by trial and error to $\omega_o$ = 10 rad/s, and ζ = 0.7.

## PID Control

The dynamic behavior of manipulator robot with 7 DOFs can be expressed in the joint space using the Newton-Euler approach:

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

Where, $M(\theta)$ is the $n \times n$ mass matrix, $V(\theta, \dot{\theta})$ is an $n \times 1$ vector of centrifugal and Coriolis terms, $G(\theta)$ is an $n \times 1$ vector of gravity terms and $F(\theta, \dot{\theta}) \epsilon \mathbb{R}^n$ is the vector of nonlinear coulomb friction.

The general layout of the PID control approach used for UWM-SREx is depicted in Fig. 7. The joint torque commands are expressed by the equation:

$$\tau = K_P(\theta_d - \theta) + K_V(\dot{\theta_d} - \dot{\theta}) + K_I \int (\theta_d - \theta) dt$$

Where, $\theta_d, \theta \epsilon \mathbb{R}^n$ are the vector of desired and measured joint angles, $\dot{\theta_d}, \dot{\theta} \epsilon \mathbb{R}^n$ are the vector of desired and measured joint velocities, $K_P$, $K_V$, $K_I$ are the diagonal definite gain matrices.

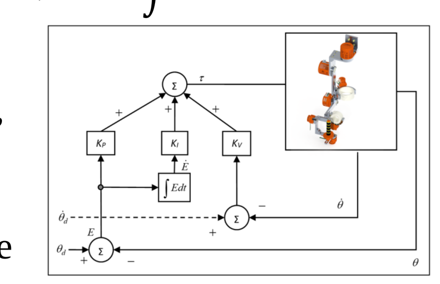


*Fig. 7. The PID control layout*

## Experimental Results

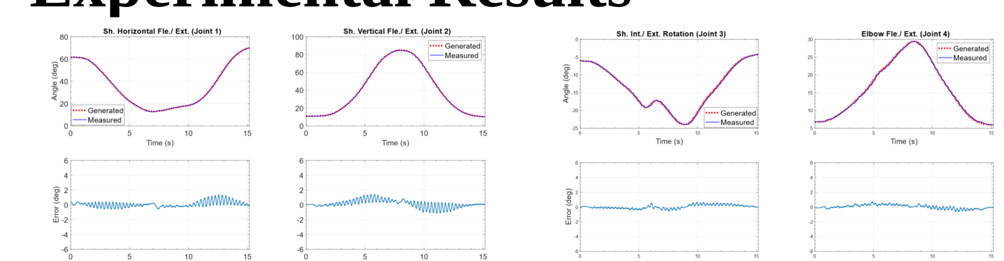



*Fig. 8. Kinect generated trajectories for four joints and UWM-SREx tracking with PID controller*

Fig. 8. shows the experiment results. In this experiment, the subject's non-impaired arm performs a diagonal reaching motion. From these results, it is observed that the Kinect generated trajectories consist of four DOF (at the level of shoulder and elbow joint) for diagonal reaching motion. Therefore Kinect generated trajectories are more realistic. Also, from the plot of position tracking error, it is seen that the tracking error for any of the four joints remains less then ±5° . The PID controller shows good tracking performance. More accurate tracking can be achieved by implementing a more sophisticated nonlinear controller.

## Conclusions

In this research, a vision-based motion imitation system using a Kinect sensor and UWM-SREx robot is developed to provide mirror therapy. An inverse kinematic solution to map the subject upper arm joint coordinates with the robot joint angles was developed based on the geometric approach. Experimental results revealed that a low-cost marker-less motion sensor (Kinect sensor) can be effectively used to generate motion trajectories by tracking joint coordinates of a functional upper arm.

## Literature cited

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## For further information

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