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A Kinematic Model of an Upper Limb Rehabilitation Robot System

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***Abstract* - This paper presents a kinematic model of an upper limb rehabilitation robot system based on Denavit-Hartenberg parameters method. The system possesses advantages of less weight, compact size, and interaction in the rehabilitation process. Furthermore it can provide a sufficient work room for the patient's upper limb. This system mainly consists of an upper limb exoskeleton rehabilitation device (ULERD), a haptic device called PHANTOM Premium, and an interactive virtual reality environment. The proposed rehabilitation robot system is a master-slave system. The impaired hand is hard bolted to the ULERD, so the doctor (or the intact hand of patients) can move the stylus of PHAMTOM Premium and guide the injured hand to move along some predefined training track. This paper aims to establish a kinematic model of the rehabilitation robot system. A kinematic model focusing on the ULERD and the PHANTOM Premium is built to ensure the consistency for both the Phantom side and ULERD side. DH-parameters-based modeling can be an effective method in kinematic modeling of a robot.**

Key words: ULERD, DH parameters, Kinematic model, Rehabilitation

I. INTRODUCTION

At present, stroke and cerebrovascular accident are the leading cause of illness especially common in old people. Physiologically functional disorder caused by apoplexy directly influences the quality of the sufferers' life, especially when the person is suffering from hemiplegia after stroke. These patients cannot move their upper limb freely. There are two ways in rehabilitation: one is traditional rehabilitation, the other new rehabilitation. The traditional rehabilitation mainly depends on the experience of recovery physiotherapists. The new rehabilitation mainly adopts rehabilitation robots in training task. Especially, upper limb rehabilitation robots are employed widely for their efficacy and economy.

In 1991, MIT-Manus was developed by Hermano I Krebs which is the first one of famous upper limb rehabilitation robot and offering a highly back-drivable mechanism with a soft and stable feel for the user [1]. A robot named ARM-Guide was implemented by Reinkensmeyer in 1991. An improved diagnostic tool for assessing arm movement impairment after brain injury and a therapeutic tool for exploring the effects of active assist therapy were provided by ARM-Guide [2]. The Mirror Image Movement Enabler (MIME) was designed in Stanford University. A novel method of providing movement therapy which combines bimanual movements with unilateral passive, active-assisted, and resisted movements of the hemiparetic upper limb was tested with MIME [3]. Different with robots mentioned above, Gentle/s had made enjoyable effect in clinical application due to a virtual reality system where virtual subjects can be manipulated [4], [5]. A new semi-exoskeleton robot with six degrees of freedom (DoFs) called ARMin for arm rehabilitation has been designed by Nef in university Zurich in 2007 [6].

In China, scientists and researchers focused on the researches about rehabilitation robots. Yuchuan Hu designed an upper limb compound training rehabilitation robot [7]. A rehabilitation robot with force-position hybrid fuzzy controller was designed in National Cheng Kung University in Taiwan. The robot can guide patient's wrist to move along planned linear or circular trajectories [8]. A novel Internet based tele-rehabilitation exercise manipulator was presented in Southeast University. The doctor could remotely control the manipulator to help the upper limb injured [9]. The Rehab-robot was developed by Tsai in National Taiwan University in 2010. This exoskeleton can be used for the rehabilitation of the patients and capable of generating some degrees of freedom at each joint [10].

Although some upper limb rehabilitation systems have been developed, but there is few researches focusing on forward kinematic modeling. The novelty of the paper lies in establishing a precise model based on DH parameters method for upper limb rehabilitation robot system, whose joints mainly consists of revolute joints and prismatic joints.

This paper is organized as follows. Some relative researches about upper limb rehabilitation robots are introduced first in section I. An Upper Limb Exoskeleton Rehabilitation Device (ULERD) and PHANTOM Premium 1.5 which consists of the master-slave rehabilitation system will be showed respectively in section II. DH parameters method is introduced in section III. Forward kinematics for the robot system is provided in section IV. Some experiments are carried out for evaluating the accuracy of proposed model in section V. The last section presents some conclusions.

II. EXPERIMENTAL SYSTEM

A. The Upper Limb Exoskeleton Rehabilitation Device (ULERD)

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The ULERD aims to provide effective training to the patients with motor dysfunction to recover the motor function of upper limb including elbow and wrist joints. The ULERD is ergonomically comfortable. Meanwhile, it is the aim to design such a wearable and portable device. Design process of ULERD can be obtained in detail from reference [11]. The structure of the ULERD from upper view is showed in Fig. 1. ULERD has three active DoFs including the elbow flexion/extension, forearm pronation/supination and wrist flexion/extension.

Due to comfortable and suitable for home-rehabilitation to patients, mass-reduction of the device is required. BLDC motor (Maxon Technology) used in the ULERD for its high power density to decrease the mass of the device. Main frames of this device are made of aluminum board. The total weight is only 1.3kg.

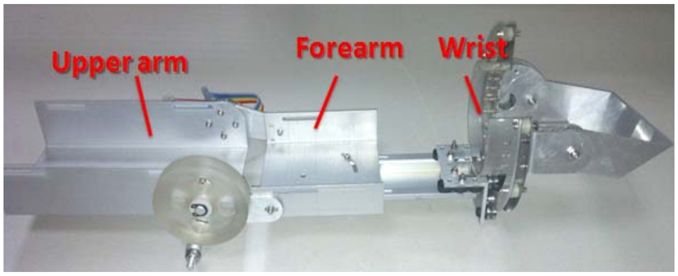

Fig. 1 The prototype of the upper limb exoskeleton rehabilitation device

B. Haptic Device (PHANTOM Premium 1.5)

As a master part manipulated by doctor, PHANTOM Premium 1.5 is applied in the system successfully providing force feedback to the stylus (Fig. 2). The large workspace of the product (19.5x27x37.5cm) is a guarantee of moving upper limb in a big space.

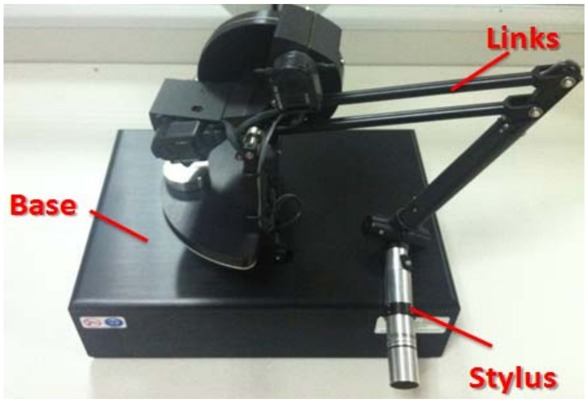

Fig. 2 PHANTOM Premium1.5 haptic device（SensAble Technologies）

C. Operation Principle of The Robot System

The upper limb rehabilitation robot system proposed in the paper is a master-slave system in which the master part is the PHANTOM Premium and the slave part is ULERD [12] [13]. The system composition is shown in Fig. 3. The slave part coordinates with the master part through a PC-based virtual reality environment (Fig. 4). The impaired hand is hard bolted to the ULERD, so the rehabilitation therapist can move the stylus of PHAMTOM Premium and guide the injured hand to move along certain of predefined training track [14].

In order to keep safe and assess the experimental results, a force sensor is fitted to the forearm plate by which can detect the general contact force. The MTx sensor is chosen to get the accurate pose information of patient's impaired hand [15].

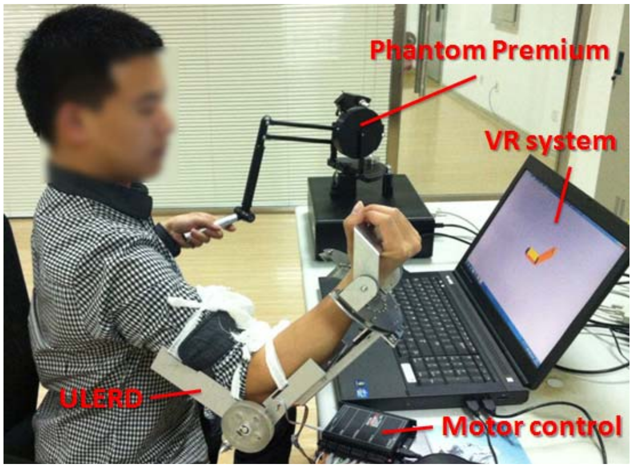

Fig. 3 The upper limb rehabilitation robot system composition

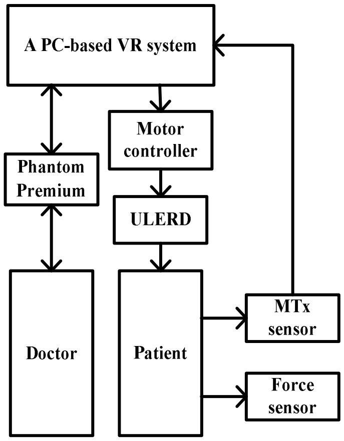

Fig. 4 Block diagram of the upper limb rehabilitation robot system

Ⅲ. THE DENAVIT-HARTENBERG PARAMETERS

The forward kinematics is the relationship between the lost coordinate frame and the base coordinate frame. In this section, the promised description DH parameters method is introduced to describe the link and its connections to the next or previous link.

To describe these two coordinate frames, four parameters are needed. In fact, Denavit-Hartenberg parameters are four parameters: a_i, α_i, d_i, θ_i (Fig. 5). As shown in Fig .5, two links and three axes are presented. Basically, the distance a_i, α_i describe that link I, d_i, θ_i describe how a link is connected to the next one.

The meanings of four parameters are listed as follows:

1) The distance of two links a_i: distance (Z_i, Z_{i+1}) along X_i.

2) Angle between two links α_i: angle (Z_i, Z_{i+1}) about X_i.

3) d_i: distance (X_{i-1}, X_i) along Z_i

4) θ_i: angle (X_{i-1}, X_i) about Z_i

Among these four parameters, one of them is variable. In the case of prismatic joints, θ_i will be the variable. In the case of revolute joints, d_i will be the variable [16].

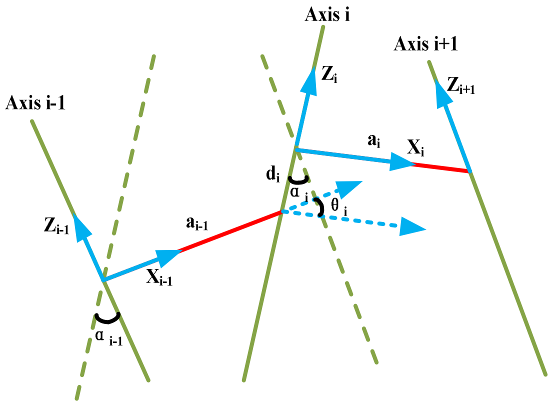

Fig. 5 Diagram of the Denavit-Hartenberg notation

DH parameters can be found after establishing joint coordinate frames. The transform matrix from J_i to J_{i-1} can be obtained from

$$T_i^{i-1} = Rot(x_{i-1},\alpha)\cdot Trans(a,0,0)\cdot Rot(Z_i,0)\cdot Trans(0,0,d)$$

$$= \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where $c\theta_i$, $s\theta_i$ refer to $\cos\theta_i$, $\sin\theta_i$ respectively..

Ⅳ. THE FORWARD KINEMATICS FOR THE ROBOT SYSTEM

A. Forward Kinematics For the ULERD

The typical way to describe the schematic kinematics of a robot is applied in the forward kinematics analysis of ULERD (Fig. 6). The letter R represents a revolute joint, P represents a revolute joint. According to establishment principles of joint coordinate frames mentioned above, the origins and coordinate frames are assigned at the proper positions.

As shown in Fig. 6, four joint coordinate frames are assigned on the ULERD which assigned along Z axis, including three revolute joints and one prismatic joint.

As shown in Fig. 7, Z_0, Z_1 and Z_4 are coming out of the plane at their revolute joints. And the sliding joint here which slides along Z_2 is a prismatic joint. This representation is proper and effective to compute the forward kinematics simply.

Before the workspace of ULERD is analysed, it is necessary to image the three dimensional motion of this mechanism and find the volume that is span by the end-effectors' motion.

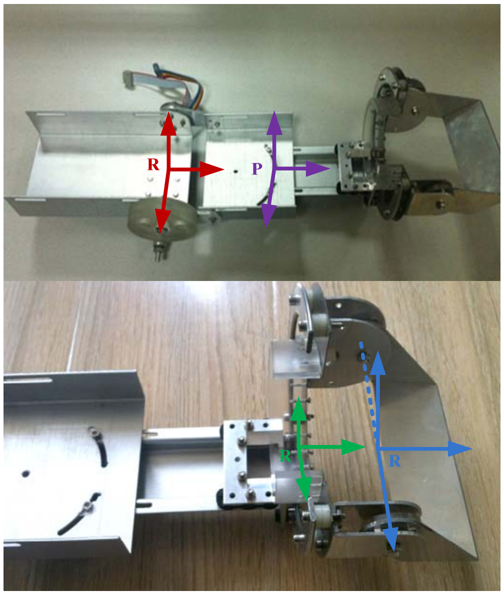

Fig. 6 Joints of upper limb exoskeleton Rehabilitation Device

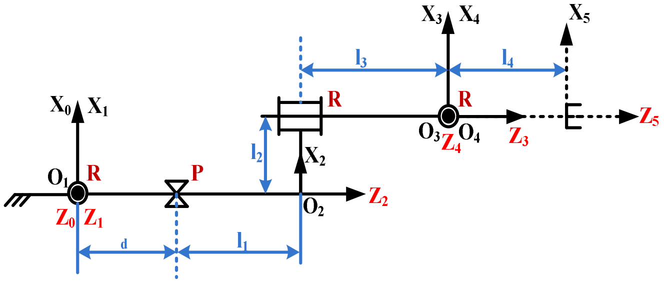

Fig. 7 Schematic kinematics of upper limb exoskeleton Rehabilitation Device

TABLE I shows all the DH parameters when ULERD is in the initial configuration, demonstrated in Fig. 7. As mentioned, the definition of four DH parameters and the rule of signs can be applied to compute these parameters of joints. (l_1=8.30mm, l_2=6.30mm, l_3=3.55mm, l_4=7.50mm)

TABLE I

DH PARAMETERS OF JOINTS

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	90	0	$d+l_1$	0
3	0	l_2	l_3	θ_2
4	-90	0	0	θ_3
5	90	0	l_4	0

After finding the forward kinematics for ULERD, a sub-transformation matrices associated with the DH parameters are computed to find the entire transformation matrices, which is adopted to determine X, Y and Z(i.e. the prismatic joint location) and orientation(i.e. the joint angles) of the end-effector. The transformation matrix from i to i-1 is calculated as follow.

$$T_1^0=\begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_2^1=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & -d-l_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^2=\begin{bmatrix} c_2 & -s_2 & 0 & l_2 \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 1 & l_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_4^3=\begin{bmatrix} c_3 & -s_3 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ -s_3 & -c_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_5^4=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & -l_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

To compute the forward kinematics, multiplication is adopted to calculate the entire transformation matrix from N to frame 0. The entire transformation matrix is gives by:

$$T_k^0=T_1^0T_2^1\cdots T_{k-1}^kT_k^{k-1} \tag{2}$$

The entire transformation matrix of each joint is gives by:

$$T_2^0=\begin{bmatrix} c_1 & 0 & s_1 & s_1(d+l_1) \\ s_1 & 0 & -c_1 & -c_1(d+l_1) \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^0=\begin{bmatrix} c_1c_2 & -c_1s_2 & s_1 & c_1l_2+s_1(d+l_1+l_3) \\ s_1c_2 & -s_1s_2 & -c_1 & s_1l_2-c_1(d+l_1+l_3) \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_4^0=\begin{bmatrix} c_1c_2c_3-s_1s_3 & -c_1c_2s_2-c_3s_1 & c_1s_2 & c_1l_2+s_1(d+l_1+l_3) \\ s_1c_2 & -s_1s_2 & -c_1 & s_1l_2-c_1(d+l_1+l_3) \\ s_2c_3 & -s_2s_3 & -c_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_5^0=\left[\begin{array}{ccc:c} c_1c_2c_3-s_1s_3 & c_1s_2 & c_1c_2s_3+c_3s_1 & T_{px} \\ s_1c_2 & -s_1s_2 & s_1s_3c_2-c_1c_3 & T_{py} \\ s_2c_3 & -c_2 & s_2s_3 & T_{pz} \\ \hdashline 0 & 0 & 0 & 1 \end{array}\right]=\left[\begin{array}{c:c} T_R & T_p \\ \hdashline 0 & 1 \end{array}\right]$$

$$T_p=\begin{bmatrix} l_4c_1c_2s_3+c_1l_2+s_1(d+l_1+l_3+l_4c_3) \\ l_4s_1s_3c_2+s_1l_2-c_1(l_4c_3+d+l_1+l_3) \\ l_4s_2s_3 \end{bmatrix} \tag{3}$$

where T_R represents the rotation of frame five respect to frame zero. T_P stands for the origin of frame five in frame zero.

B. *Forward Kinematics For The Upper Limb*

DH parameters method is also used to develop a kinematic model of upper limb. The origins and coordinate frames are assigned at the proper positions. (Fig. 8)

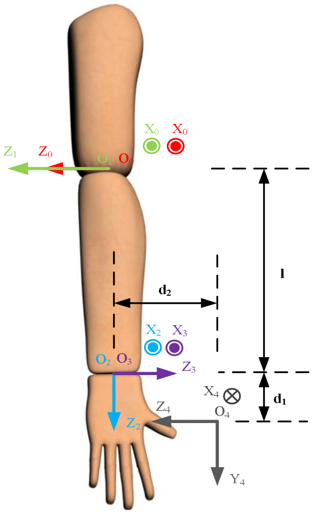

Fig. 8 Kinematics of the upper limb

TABLE II shows DH parameters when upper limb is in the initial configuration, demonstrated in Fig. 8. (l=230mm, d_1=60mm, d_2=80mm)

TABLE II
DH PARAMETERS OF JOINTS

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	90	0	1	θ_2
3	90	0	0	θ_3

The transformation matrix from i to i-1 is calculated as follow:

$$T_1^0=\begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_2^1=\begin{bmatrix} c_2 & -s_2 & 0 & 0 \\ 0 & 0 & -1 & -l \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^2=\begin{bmatrix} c_3 & -s_3 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_4^3=\begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & -1 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

The forward kinematics for the upper limb can be computed from:

$$T_4^0=\begin{bmatrix} -c_1c_2c_3-s_1s_3 & -c_1c_2s_3+s_1c_3 & -c_1s_2 & d_1(-c_1c_2s_3+s_1c_3)+c_1s_2d_2+s_1l \\ -s_1c_2c_3+c_1s_3 & -s_1c_2s_3-c_1c_3 & -s_1s_2 & d_1(-s_1c_2s_3+c_1c_3)+s_1s_2d_2-c_1l \\ -s_2c_3 & -s_2s_3 & c_2 & -s_2s_3d_1-c_2d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

C. *Forward Kinematics For The PHANTOM*

Similarly, the forward kinematics of PHANTOM is computed from the base to the end-effector. Fig. 9 shows one coordinate frame for the base and six coordinate frames for each link.

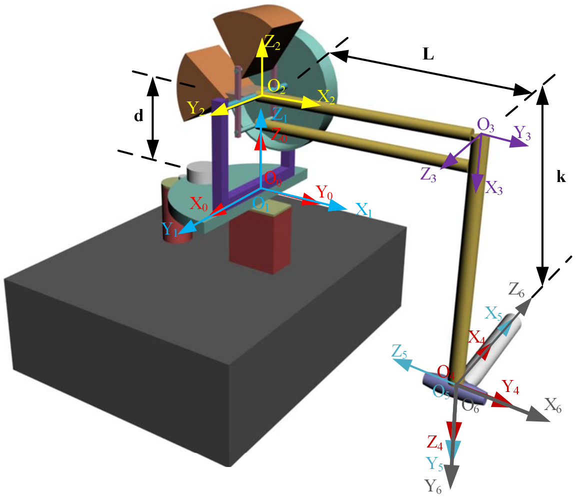

Fig. 9 Kinematics of the PHANTOM

The transformation matrix for the PHANTOM can be obtained as follow. (d=90mm, L=200mm, k=210mm)

$$T_1^0 = \begin{bmatrix} -s_1 & c_1 & 0 & 0 \\ c_1 & s_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_2^1 = \begin{bmatrix} c_2 & -s_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ s_2 & c_2 & 0 & d \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^2 = \begin{bmatrix} s_3 & c_3 & 0 & L \\ -c_3 & s_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_4^3 = \begin{bmatrix} 0 & 0 & 1 & k \\ s_4 & c_4 & 0 & 0 \\ -c_4 & s_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_5^4 = \begin{bmatrix} c_5 & -s_5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s_5 & c_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_6^5 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ s_6 & c_6 & 0 & 0 \\ -c_6 & s_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_6^0 = T_1^0 T_2^1 T_3^2 T_4^3 T_5^4 T_6^5 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

where

$$a_x = \text{-}(c_{(2+3)} s_1 s_4 + c_1 c_4) c_5 \text{-} s_{(2+3)} s_1 s_5$$

$$a_y = (\text{-}c_{(2+3)} c_1 s_4 \text{-} s_1 c_4) c_5 + s_{(2+3)} c_1 s_5$$

$$o_x = ((c_{(2+3)} s_1 s_4 + c_1 c_4) s_5 \text{-} s_{(2+3)} c_5) s_1 c_6 + (c_{(2+3)} s_1 c_4 \text{-} c_1 s_4) s_6$$

where $c_{(2+3)} = \cos(\theta_2 + \theta_3)$ and $s_{(2+3)} = \sin(\theta_2 + \theta_3)$.

D. *Forward Kinematics For The PHANTOM And Upper Limb*

Coordinate frames are assigned when manipulator handles the end-effector of the Phantom Premium with his left hand in Fig. 10.

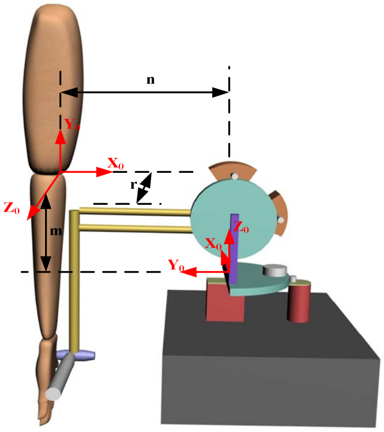

Fig. 10 Kinematics of the PHANTOM and the upper limb

From Fig. 10, the transformation matrix from the original of the upper limb to the Phantom Premium is

$$T_U^P = \begin{bmatrix} 0 & 0 & -1 & -r \\ -1 & 0 & 0 & n \\ 0 & 1 & 0 & m \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

where n, r and m stand for the displacements between original of Phantom Premium and upper limb along x, y and z axis respectively. (n=200mm, r=40mm, m=160)

Furthermore, the transformation matrix from the coordinate frame 4 to the Phantom Premium is

$$T_4^P = T_U^P T_4^0 =$$

$$\begin{bmatrix} s_2 c_3 & s_2 s_3 & -c_2 & s_2 s_3 d_1 + c_2 d_2 - r \\ c_1 c_2 c_3 + s_1 s_3 & c_1 c_2 s_3 - s_1 c_3 & c_1 s_2 & d_1(c_1 c_2 s_3 - s_1 c_3) - c_1 s_2 d_2 - s_1 l + n \\ c_1 s_3 - s_1 c_2 c_3 & -s_1 c_2 s_3 - c_1 c_3 & -s_1 s_2 & d_1(-s_1 c_2 s_3 - c_1 c_3) + s_1 s_2 d_2 - c_1 l + m \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

Due to $T_4^P = T_6^0$, we can calculate θ_1, θ_2, θ_3 as follows:

$$\theta_1 = \arccos(a_y / s\theta_2) \tag{8}$$

$$\theta_2 = \arccos a_x \tag{9}$$

$$\theta_3 = \arcsin(o_x / s\theta_2) \tag{10}$$

Therefore, the angle of the elbow flexion/extension, forearm pronation/supination and wrist flexion/extension can be obtained.

E. *Model Validation*

The joint angle and position of ULERD is measured. The true x position of J_5 and computed x position in the model is shown respectively in Fig. 11. The vertical axis stands for the x position, and the horizontal axis stands for θ_3. The dotted line represents the true x position of J_5, the solid line represents computed x position in the model. The computed position in the model is close enough to the true position, from the error between two positions in Fig. 12.

Therefore, the model can provide the accurate pose information of ULERD.

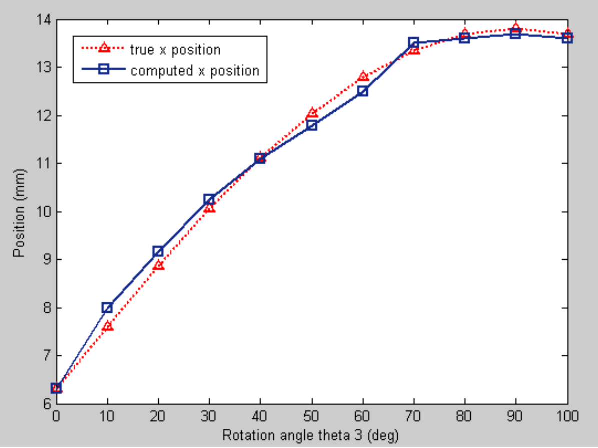

Fig. 11 Line graph of x position

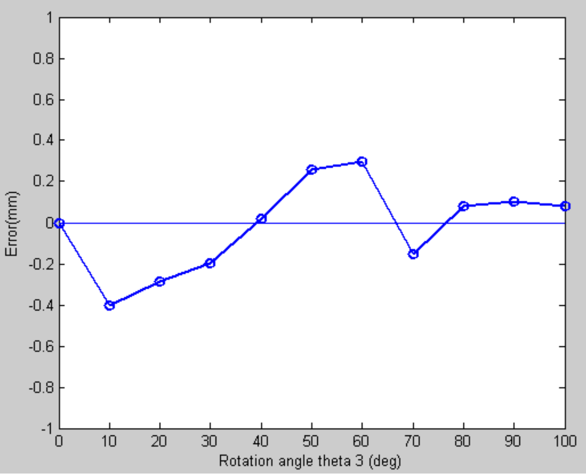

Fig. 12 Line graph of error between x positions

IV. CONCLUSION AND FUTURE WORK

In this paper, a master-slave rehabilitation system which possessed the PHONTOM Premium and the ULERD was introduced. Forward kinematics was necessary and essential to obtain the position and posture of the joints of ULERD and PHANTOM. This paper aimed at setting up a kinematic model of the system. The following conclusions can be drawn:

1) A method based on DH parameters to build kinematic model of robots was presented, which included building joint links by DH rule, setting up joint coordinate frames, finding DH parameters. Forward kinematics for the ULERD, the PHANTOM and upper limb were analyzed.

2) The motion of 3 DOFs including the elbow flexion/extension, forearm pronation/supination and wrist flexion/extension in the ULERD had been computed by variables and parameters of the PHANTOM and upper limb.

3) Experiment had been carried out to prove that the model of ULERD was accurate to describe the system characteristics.

The kinematic model of the system provided the pose information of the whole master-slave system. The proposed model applied in the tracking control should take into consideration in the future.

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