3D modelling and simulation of human upper limb

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Abstract. In this paper we analyse the kinematics and dynamics of the human upper limb to determine the position and the orientation of the shoulder and elbow joints in accordance with the forward and reverse kinematic mathematical model and the Jacobian forward and reverse kinematic mathematical model. We also developed a 3D human arm model in a computer aided-design software based on the result determined from mathematical models and in accordance with five degrees of freedom offered by anatomical position of human arm revolute joints associated to the shoulder and elbow. We simulated the entire dynamics of human arm in Matlab-Simulink in order to control the movement according to different predefined trajectories.

1. Introduction
An accurate estimation of human upper limb kinematics is essential for clinical applications that involving the study of joints motion to discover potential medical pathologies such as musculoskeletal stiffness or slack muscle disorder [1] and also for neurological rehabilitation based on anthropomorphic robots development such as 3D printed prosthetics of the upper limb designed to replace lost function of human arm in case of amputation [2] or exoskeletons for human upper limb with passive joints used to help patients to recover from stroke disease in a manner that are able to diminish physical therapists’ workloads and in the same time to compensate for deficiencies of manual rehabilitation [3]. In this case the development of human arm kinematic model is absolutely necessary due to the fact that in the design of the exoskeleton for the upper limb the kinematic joints near the elbow and the wrist should always be in the same position as the elbow or the wrist of the upper limb.

Regarding the functional anatomical structure, the organic form of the human arm consists of two rotation kinematic couplers that compose shoulder joint and the elbow joint if we consider the joint of the wrist as fixed. The kinematic coupling of the shoulder consists of three bones in order the humerus, scapula and clavicle with four joints (Figure 1): the glenohumeral joint that have two spherical contact surfaces, first the glenoid cavity and second the humeral head that connecting the humerus to scapula; the sternoclavicular joint that connects the thorax with clavicle; the acromioclavicular joint that connects the scapula acromion to the sideways part of the clavicle; the scapulothoracic joint that are not consist of articular structure, instead the sliding movement between scapula and thorax are constrained only by the surrounding muscles [4]. The glenohumeral joint due to its instable bony structure plays an important role in ensuring a wide range of shoulder motion: abduction at an angle between 150-180°, flexion at angle of 180°, extension at an angle between 45-60° and internal external rotation at an angle of 90° [5].
Figure 1. Anatomical structure of the shoulder [6].

From the anatomical point of view, the elbow is connected from the joint of the shoulder through the humerus bone and comprises two more bones: the ulna and the radius, all of them surrounded by a joint capsule [7] as presented in Figure 2.

Figure 2. Anatomical structure of the elbow.

Regarding the kinematic coupling of the elbow, it plays an important role in the flexion motion of the arm at an angle between 140-160°, in the extension motion of the arm at an angle between 0-10°, in the pronation of the forearm at an angle between 80-90° and in the supination of the forearm at an
angle of 90° [8]. It also offers slight lateral and medial mobility based on abduction and adduction movements in the frontal plane.

2. Human arm kinematic model

Based on the organic form of the human upper limb it can be deduced the simplified form could be represented as an open cinematic chain as shown in Figure 3 that having three elements and two kinematic couplings, the coupling of the shoulder being a spherical rotation coupling, and the coupling of the elbow being a cylindrical coupling.

In order to calculate the degrees of freedom (DoF) of the human upper limb in must be determined the maximum number of movements that each kinematic couple can achieve [10].

![Figure 3. Simplified form of the kinematic chain of human upper limb.](image)

In the case of the shoulder due to the fact that the working space represented by the total points through which the characteristic point may pass is the spherical type, the maximum number of allowed movements is equal to three. So, the kinematic coupling of the shoulder it allow three rotation movement along x, y and z axis that coincide [10].

Next, the kinematic chain that continues with the elbow due to the reason that the workspace is described by a cylinder it allows two rotation movement along y and z axis that coincide with two degrees of freedom.

First, it was determined the direct Denavit-Hartenberg (DH) model (Table 1), based on the reference frames from Figure 3 and the resulting DH parameters table below.

| Element | $a_i$ | $\alpha_i$ | $d_i$ | $\theta_i$ |
|---------|-------|------------|-------|------------|
| 1       | 0     | $\pi/2$    | 0     | $\pi/2 + \theta_1$ |
| 2       | 0     | $\pi/2$    | 0     | $\pi/2 + \theta_2$ |
| 3       | 0     | 0          | 0     | $\theta_3$ |
| 4       | 0     | $\pi/2$    | $d_3$ | $\pi/2 + \theta_4$ |
| 5       | $d_5$ | 0          | 0     | $\theta_5$ |
Replacing the parameters values from the DH table in the formula of $T_{0,5}$ and multiplying the resulting matrixes we get the $T_{0,5}$ matrix that represents the direct DH model. The last column gives the position of the arm wrist and the first three column its orientation.

$$
T_{0,5} = \begin{bmatrix}
-s_1s_2s_{3+4}c_5 + c_1c_{3+4}c_5 - s_1c_2s_5 & s_1s_2s_{3+4}s_5 - c_1c_{3+4}s_5 - s_1c_2c_5 & s_1c_2c_{3+4} + c_1s_{3+4} & X_5 \\
-c_1s_2s_{3+4}c_5 - s_1c_{3+4}c_5 + c_1c_2c_5 & -c_1s_2s_{3+4}s_5 - s_1c_{3+4}s_5 + c_1c_2c_5 & -c_1c_2c_{3+4} + s_1s_{3+4} & Y_5 \\
0 & c_2s_{3+4} & 0 & Z_5 \\
\end{bmatrix}
$$

(1)

$$
\begin{cases}
X_5 = d_5(-s_1s_2s_{3+4}c_5 + c_1c_{3+4}c_5 - s_1c_2s_5) - d_3s_1c_2 \\
Y_5 = d_5(c_1s_2s_{3+4}c_5 + s_1c_{3+4}c_5 + c_1c_2s_5) + d_3c_1c_2 \\
Z_5 = d_5(-c_2s_{3+4}c_5 + s_2s_5) + d_3s_2
\end{cases}
$$

(2)

In order to compute the inverted DH model, we impose a position and orientation to be reached by the arm wrist, and based on the above matrix we determine the movement angle for each joint of the human arm.

We get the following equations:

$$
tg\theta_1 = \frac{d_5 \cdot r_{11} - X_5}{Y_5 - d_5 \cdot r_{21}}
$$

(3)

$$
tg\theta_2 = \frac{Z_5 - d_5 \cdot r_{31}}{\sqrt{(d_5 \cdot r_{11} - X_5)^2 + (Y_5 - d_5 \cdot r_{21})^2}}
$$

(4)

$$
tg(\theta_3 + \theta_4) = \frac{r_{12} \cdot (Y_5 - d_5 \cdot r_{21}) + r_{23} \cdot (d_5 \cdot r_{11} - X_5)}{r_{33} \cdot d_3}
$$

(5)

$$
\theta_5 = -\arcsin \frac{C}{\sqrt{A^2 + B^2}} + atg \frac{A}{B}
$$

(6)

As can be noticed, the angles $\theta_3$ and $\theta_4$ are determined together as they are performing a rotation around the same axis.

3. Dynamic Jacobian Model

We have determined the direct DH model and based on this we can determine the position of the arm wrist. If we need to know the linear and angular speeds of the wrist due to the movement of each joint, we develop the Jacobian model of the human arm.

The direct Jacobian refers to:

$$
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{z} \\
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix}
= \begin{bmatrix}
J_1 & J_2 & J_3 & J_4 & J_5
\end{bmatrix}_{6x5}
\begin{bmatrix}
\dot{\theta}_1 \\
\dot{\theta}_2 \\
\dot{\theta}_3 \\
\dot{\theta}_4 \\
\dot{\theta}_5
\end{bmatrix}
$$

(7)

where:
\[ J_1 = \begin{bmatrix} -y_5 \\ x_5 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \]  
(8)

\[ J_2 = \begin{bmatrix} S_1 \cdot Z_5 \\ -c_1 \cdot Z_5 \\ c_1 \cdot y_5 - S_1 \cdot x_5 \\ c_1 \\ S_1 \\ 0 \end{bmatrix} \]  
(9)

\[ J_3 = \begin{bmatrix} c_1 \cdot c_2 \cdot Z_5 - S_2 \cdot y_5 \\ S_2 \cdot x_5 + S_1 \cdot c_2 \cdot Z_5 \\ -S_1 \cdot c_1 \cdot y_5 - c_1 \cdot c_2 \cdot x_5 \\ -S_1 \cdot c_2 \\ c_1 \cdot c_2 \\ S_2 \end{bmatrix} \]  
(10)

\[ J_4 = \begin{bmatrix} d_5(c_1 \cdot s_3 + c_5 + S_1 \cdot S_2 \cdot c_3 + c_5) \\ d_5(-S_1 \cdot s_3 + c_5 + S_1 \cdot S_2 \cdot c_3 + c_5) \\ d_5(c_2 \cdot c_3 + c_5) \\ -S_1 \cdot c_2 \\ c_1 \cdot c_2 \\ S_2 \end{bmatrix} \]  
(11)

\[ J_5 = \begin{bmatrix} d_5(-c_1 \cdot s_3 + s_5 - S_1 \cdot c_2 \cdot c_5 + S_1 \cdot S_2 \cdot c_3 + s_5) \\ d_5(c_1 \cdot c_3 + c_5 + S_1 \cdot S_2 \cdot c_3 + c_5) \\ d_5(s_2 \cdot s_3^2 + S_1 \cdot S_2 \cdot c_3 + c_5) \\ S_1 \cdot S_2 \cdot c_3 + c_5 \\ -c_1 \cdot S_2 \cdot c_3 + c_5 \\ c_2 \cdot c_3 \end{bmatrix} \]  
(12)

If we impose a certain speed profile for hand wrist, we would determine the speed of each couple through:

\[
\begin{bmatrix}
\dot{\theta}_1 \\
\dot{\theta}_2 \\
\dot{\theta}_3 \\
\dot{\theta}_4 \\
\dot{\theta}_5
\end{bmatrix} = J^{-1} \begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{z} \\
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix}
\]  
(13)

But, \( J_{6 \times 5} \) has the rank at most 4 that is less than \( \min(6,5) \), so it is not full rank and pseudoinverse cannot be calculated without imposing some restrictions.

**4. 3D model design**

The 3D model of the human arm has been created according to the anatomical placement of joints for the upper right limb in a way to ensure five degrees of freedom. There was used SolidWorks, a computer aided design software that allows to design 3D parts from 2D sketches with the advantage of being able to combine them into an assembly project and detail into a 2D drawing [9].
In order to be able to import the 3D model in MatLab Simulink and use it successfully in modelling and simulation of human arm movement, there was considered the right arm attached to the torso, that was also modelled in SolidWorks. The front plane view of the torso is presented in Figure 4.

![Torso front view](image)

**Figure 4.** Torso front view.

All the parts of the human arm were designed together with a representation of the two useful joints, the shoulder and elbow, as can be seen in Figure 5.

![Human arm elements](image)

**Figure 5.** Human arm elements.

The shoulder consists of three rotation joints all located in the same place and the elbow consists of two rotation joints also located in the same place.
5. Results
The 3D model of the human arm was imported into MatLab-Simulink and added the movement of each coupling along imposed trajectories together with the direct DH mathematical model. In Figure 6 the MatLab-Simulink model is presented.

![Simulation model](image)

**Figure 6.** Simulation model.

On the basis of the trajectories required for the movement of each arm coupling, one can follow the movement of the arm final element.

![Simulation result](image)

**Figure 7.** Simulation result.

In Figure 7 is presented arm position after moving with angles 45°, 30°, 90°, 30° and 45°.
6. Conclusions
Among the advantages of the human arm models and simulations are the workspace if the arm and forearm lengths are known. Simulation can determine the movement limits of the human arm without endangering any human subject.

In modelling and simulation, the velocity of the wrist motion can be determined by the movement of each coupling.

Another advantage of using the models is that once the trajectory is known and the speed of movement can be used for the robotic arms that have to perform a movement similar to that of the human arm.

7. References
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