A Robotic Exoskeleton Assistive Device: Design and Kinematic Analysis of a Hand Exoskeleton for Assistance

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Abstract. Addressing the challenges faced by individuals with motor disabilities, which impedes ease in movement, coordination, or sensation, a low-weight hand exoskeleton was developed considering accessibility, low cost, adaptability, and mass manufacturing to overcome the impact of hand functioning disorders on people's physical and social well-being. In this paper, a 12-DOF Hand exoskeleton consisting of a 6-DOF Arm and 6-DOF finger exoskeleton was designed and later its kinematic analysis was performed. By taking into consideration the constraints provided by the exoskeleton to human hand motion, the Forward kinematics, using Denavit-Hartenberg (D-H) parameters were conducted to determine its workspace.

1 Introduction

The evolution of exoskeleton robotics has garnered significant attention in recent times. While the concept of it dates to the late 1800s, the pioneering success of the Hardiman exoskeleton [1] in the 1960s marked a milestone in the field. Initially designed for military purposes to augment strength and performance, the Hardiman utilized a master-slave configuration with hydraulic actuators.

Subsequent advancements, such as the upper-limb exoskeleton introduced by Kazerooni et al [2], emphasized physical human-robot interaction (pHRI), paving the way for direct mechanical power transmission without a master-slave system. Additionally, the University of Tsukuba's development of the Hybrid Assistive Limb (HAL) showcased the potential for assisting impaired individuals, both in daily life and industrial settings [3]. ADL was designed for consumer use, but later versions were also created for industrial use.

Over the past two decades, there has been a remarkable surge in the utilization of upper-limb exoskeletons, garnering considerable attention from both the biological and technical communities. This technology is increasingly being recognized as a promising solution for individuals facing physical challenges or disabilities. [4] Ekos Vest and FORTIS [5] are two systems that have been designed to boost the wearer's performance and strength.

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Coming on the design of finger exoskeleton, IOTA [6] is a two degree of freedom thumb exoskeleton that can actuate the carpometacarpal (CMC) and metacarpophalangeal (MCP) joints through the actuation of flexible cables. Additionally, a novel Haptic Hand exoskeleton [7] that allows exerting-controlled forces on the fingertip of the index and thumb, along with several design solutions, was developed that gave some basic insights into the current development of finger exoskeleton.

In the exploration of the exoskeleton field, a notable gap in research, particularly in the realm of lightweight, portable exoskeletons tailored for rehabilitation, was observed. Motivated by this observation, efforts were initiated to contribute to the advancement of exoskeleton technology, with a specific focus on enhancing both active and passive rehabilitation, as well as addressing industrial applications. The journey commenced with the creation of a preliminary arm model, delving into the details of measurements, degrees of freedom, and input joints. Recognizing the complexity of finger design, with spatial constraints and a multitude of movements, developing a unique approach. The objective was to streamline efficiency by controlling a finger's complete range of movements using a single motor, thereby optimizing space utilization. Subsequently, design efforts extended to the development of a lightweight forearm and bicep arm exoskeleton, engineered for the purpose of effortlessly lifting everyday weights. The incorporation of a back support link played a pivotal role, strategically transferring the major load to the waist and thereby reducing the net weight borne by the individual. Navigating through the design intricacies, meticulously addressed joint dynamics aligned with human physiology. This culmination of design and engineering efforts resulted in an exoskeleton poised as an extension of active and passive rehabilitation, with potential applications in the industrial landscape.

The following sections delve deeper into the methodology, results, and discussions surrounding the exoskeleton design, aiming to fill a crucial gap in the evolving landscape of exoskeleton research.

2 Design of Hand Exoskeleton

The primary objective of this exoskeleton encompasses a wide range of applications, serving as assistive devices in the fields of medical rehabilitation and industries, along with defence and military applications. The foremost aim is to provide revolutionary solutions for differently abled people and those with paralysis, offering motion assistance that enhances their quality of life and promotes greater independence. Moreover, this technology has the potential to improve mobility and agility in industrial workspaces and has specific relevance for military applications. Taking these into consideration, the primary goal was to provide a lighter and more robust solution by addressing space constraints. Achieving 12 Degrees of Freedom (DOFs), consisting of 10 active DOFs and 2 passive DOFs, enhances comfort and flexibility in motion.

2.1 Finger Assembly

The design of the finger component was done considering space constraints. The limited space between each finger posed a challenge for effective individual motor control of each joint. Considering this, a design approach was adopted that enabled the coordinated movement of multiple joints of a finger using a single actuator for power transmission. This was achieved by the implementation of a combination of two four-bar link mechanisms, which facilitated the relative motion within the finger joints.
The finger assembly consists of eight links. The whole mechanism is eccentrically mounted upon the base link, which is connected to an actuator, resulting in the input rotation about the 1a axis. This input rotation causes a general motion of link 1, which was further attached to link 2. As the link 2 was making a turning pair with fixed link 8, the input from link 1 resulted in rotation of link 2 about 2a axis passing through the hinge point. The combination of the links 2, 3, 4, 8 acts as first four bar mechanisms and links 4, 5, 6, 7 acts as second four bar mechanism. In first mechanism, 2 and 4 are fixed upon 8, resulting only rotation of 2, 4 and general motion of link 3. Link 8 has been fixed upon the finger. Thus, the resultant general motion of link 3 is the motion provided to the finger. The rotation motion of link 4 acts as an input for the second four-bar mechanism and results in rotation and general motion of link 5 and 6 respectively. Here 4 and 6 are fixed upon 7. The general motion of the link 5 is the actual motion given to the finger. Thus overall, the link 1 gives output as general motion of link 3 and 5.

Here link 2 rotates about axis 2a, Link 3 rotates about axis 3a, Link 4 rotates about axis 4a, Link 5 rotates about axis 5a, and Link 6 rotates about axis 6a. In fig 1, the thumb 15, is governed by one four-bar mechanism and it is also provided with one slotted mechanism on a curved path along curved path 15a, which resembles the exact movement of a finger during enclosing and opening. By successfully coordinating all the fingers' desired motion is achieved.

2.2 Arm Assembly

In humans, the wrist has 3 DOFs, one is flexion/extension, then supination/pronation, and third one is radial deviation/ulnar deviation. Active control of flexion/extension and supination/pronation has been implemented. The flexion/extension movement was facilitated with respect to the forearm. A rope and pulley mechanism were provided to achieve twisting movement, which was attached to the forearm. The length of the rope was regulated by a motor attached to the forearm. This configuration helps in bidirectional motion control of the forearm, resulting in the twisting motion of the wrist. The forearm and upper arm were designed with a cage-like structure, so as to provide comprehensive support to the arm. The forearm was given flexion/extension movement about the elbow joint of the upper arm.
The upper arm acts as a connector for the forearm and shoulder. Its design encloses the upper portion of the limb, ensuring it doesn't impose any restrictions on shoulder movement. This whole arm assembly is mounted onto the "shoulder blade", which is meticulously designed as an assembly of three parts, taking into consideration of the natural range of motion of the human shoulder. These three components of the shoulder blade include the shoulder curve, shoulder rotor, and the shoulder rotor casing. These parts are made to provide a similar range of motion and flexibility as provided by the shoulder joint of the Scapula, Clavicle, and Humerus.

The Shoulder curve acts as the connecting link between the upper arm and the shoulder rotor. It facilitates the flexion/extension movement of the upper arm. This shoulder curve is mounted on the extreme part of the shoulder rotor, which results in internal/external rotation. The shoulder made a turning and free sliding pair with shoulder rotor casing. Together, these three elements of the shoulder blade serve as a load-transferring component, transferring the load from the arm exoskeleton to the back support. This results in an even distribution of the resulting load upon the body accommodating the need for three rotations along distinct axes at the shoulder.
3 Forward Kinematics

The kinematic analysis of the robotic hand was done using Denavit-Hartenberg (D-H) parameters to find the rotation and position vectors of the end-effector. The analysis was bifurcated into two distinct components: the arm assembly and the finger assembly. This paper predominantly focuses on the study of forward kinematics of arm assembly, considering finger assembly as the end-effector. The aim was to achieve an understanding of the arm assembly so that the range of motions and reachability of the exoskeleton could be known. Looking ahead, the plan involves delving into a kinematic analysis of the finger assembly in subsequent phases and studying different grasping strategies to assess the adaptability of the exoskeleton, resulting in improvement in versatility and applicability.

3.1 Finger Assembly

Using D-H parameter notation, four parameters are needed to describe how one frame is connected to its previous frame. These parameters are:

- $\theta$: joint angle between the links
- $d$: distance of previous joint center to next in z-direction
- $\alpha$: twist angle between joint axes
- $a$: distance of previous joint center to next center in x-direction
Table 1. D-H Parameters.

<table>
<thead>
<tr>
<th>θ</th>
<th>d</th>
<th>α</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>θ₁</td>
<td>0</td>
<td>(π/2)</td>
<td>l₁</td>
</tr>
<tr>
<td>θ₂</td>
<td>l₂</td>
<td>(π/2)</td>
<td>l₃</td>
</tr>
<tr>
<td>θ₃</td>
<td>0</td>
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<td>θ₄</td>
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<tr>
<td>θ₅</td>
<td>l₆</td>
<td>π/2</td>
<td>0</td>
</tr>
<tr>
<td>θ₆</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</table>

Next, using D-H parameters, a transformation matrix is written for each joint. Here we have considered,

\[ c_1 = \cos(θ_1), \quad c_2 = \cos(θ_2), \quad c_3 = \cos(θ_3), \quad c_4 = \cos(θ_4), \quad c_5 = \cos(θ_5), \quad c_6 = \cos(θ_6); \]

\[ s_1 = \sin(θ_1), \quad s_2 = \sin(θ_2), \quad s_3 = \sin(θ_3), \quad s_4 = \sin(θ_4), \quad s_5 = \sin(θ_5), \quad s_6 = \sin(θ_6); \]
The transformation matrix for each joint is as follows:

\[
[T_1^1] = \begin{bmatrix}
    c_2 & 0 & -s_2 & l_3 \ast c_2 \\
    s_2 & 0 & c_2 & l_3 \ast s_2 \\
    0 & -1 & 0 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[T_2^1] = \begin{bmatrix}
    c_1 & 0 & -s_1 & l_4 \ast c_1 \\
    s_1 & 0 & c_1 & l_4 \ast s_1 \\
    0 & -1 & 0 & l_2 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[T_3^2] = \begin{bmatrix}
    c_3 & -s_3 & 0 & l_4 \ast c_3 \\
    s_3 & c_3 & 0 & l_4 \ast s_3 \\
    0 & 0 & 1 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[T_4^3] = \begin{bmatrix}
    c_4 & 0 & -s_4 & l_5 \ast c_4 \\
    s_4 & c_4 & 0 & l_5 \ast s_4 \\
    0 & -1 & 0 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[T_5^4] = \begin{bmatrix}
    c_5 & 0 & s_5 & 0 \\
    s_5 & 0 & -c_5 & 0 \\
    0 & 0 & 1 & l_6 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[T_6^5] = \begin{bmatrix}
    c_6 & -s_6 & 0 & 0 \\
    s_6 & c_6 & 0 & 0 \\
    0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

The transformation matrix of the end-effector was calculated using the transformation matrices of individual joints.

\[
T_6^5 = T_1 \ast T_2 \ast T_3 \ast T_4 \ast T_5 \ast T_6
\]

\[
[T_5^4] = \begin{bmatrix}
    a_{11} & a_{12} & a_{13} & a_{14} \\
    a_{21} & a_{22} & a_{23} & a_{24} \\
    a_{31} & a_{32} & a_{33} & a_{34} \\
    a_{41} & a_{42} & a_{43} & a_{44}
\end{bmatrix}
\]

\[
a_{11} = s_6 \ast (c_4 \ast (c_3 \ast s_1 - c_1 \ast c_2 \ast s_3) - s_4 \ast (s_1 \ast s_3 + c_1 \ast c_2 \ast c_3)) + c_6 \ast (c_5 \ast (c_4 \ast (s_1 \ast s_3 + c_1 \ast c_2 \ast c_3) + s_4 \ast (c_3 \ast s_1 - c_1 \ast c_2 \ast s_3)) + c_1 \ast s_2 \ast s_5);
\]

\[
a_{12} = c_6 \ast (c_4 \ast (c_3 \ast s_1 - c_1 \ast c_2 \ast s_3) - s_4 \ast (s_1 \ast s_3 + c_1 \ast c_2 \ast c_3)) - s_6 \ast (c_5 \ast (c_4 \ast (s_1 \ast s_3 + c_1 \ast c_2 \ast c_3) + s_4 \ast (c_3 \ast s_1 - c_1 \ast c_2 \ast s_3)) + c_1 \ast s_2 \ast s_5);
\]

\[
a_{13} = s_5 \ast (c_4 \ast (s_1 \ast s_3 + c_1 \ast c_2 \ast c_3) + s_4 \ast (c_3 \ast s_1 - c_1 \ast c_2 \ast s_3)) - c_1 \ast c_5 \ast s_2;
\]

\[
a_{14} = l_6 \ast (c_4 \ast (c_3 \ast s_1 - c_1 \ast c_2 \ast s_3) - s_4 \ast (s_1 \ast s_3 + c_1 \ast c_2 \ast c_3)) + l_1 \ast c_1 \ast l_2 \ast s_1 + l_5 \ast c_4 \ast (s_1 \ast s_3 + c_1 \ast c_2 \ast c_3) + l_5 \ast s_4 \ast (c_3 \ast s_1 - c_1 \ast c_2 \ast s_3) + l_3 \ast c_1 \ast c_2 + l_4 \ast s_1 \ast l_3 + l_4 \ast c_1 \ast c_2 \ast s_5;
\]

\[
a_{21} = -s_6 \ast (c_4 \ast (c_1 \ast c_3 + c_2 \ast s_1 \ast s_3) - s_4 \ast (c_1 \ast s_3 - c_2 \ast c_3 \ast s_1)) - c_6 \ast (c_5 \ast (c_4 \ast (c_1 \ast s_3 - c_2 \ast c_3 \ast s_1) + s_4 \ast (c_1 \ast c_3 + c_2 \ast c_3 \ast s_1)) - s_1 \ast s_2 \ast s_5);
\]

\[
a_{22} = s_6 \ast (c_5 \ast (c_4 \ast (c_1 \ast s_3 - c_2 \ast c_3 \ast s_1) + s_4 \ast (c_1 \ast c_3 + c_2 \ast s_1 \ast s_3)) - s_1 \ast s_2 \ast s_5 - c_6 \ast (c_4 \ast (c_1 \ast c_3 + c_2 \ast s_1 \ast s_3) - s_4 \ast (c_1 \ast s_3 - c_2 \ast c_3 \ast s_1));
\]
\[
a_{23} = -s_5 \left( c_4 \left( c_1 s_3 - c_2 c_3 s_1 \right) + s_4 \left( c_1 c_3 + c_2 s_1 s_3 \right) \right) - c_5 s_1 s_2;
\]
\[
a_{24} = l_2 c_1 - l_6 \left( c_4 \left( c_1 c_3 + c_2 s_1 s_3 \right) - s_4 \left( c_1 s_3 - c_2 c_3 s_1 \right) \right) + l_1 \left( c_1 c_3 + c_2 s_1 s_3 \right) + l_3 c_2 s_1 - l_4 c_1 s_3 + l_4 c_2 c_3 s_1;
\]
\[
a_{31} = s_6 \left( c_2 s_5 + c_5 \left( s_2 s_3 s_4 - c_3 c_4 s_2 \right) \right) + s_6 \left( c_3 s_2 s_4 + c_4 s_2 s_3 \right);
\]
\[
a_{32} = c_6 \left( c_3 s_2 s_4 + c_4 s_2 s_3 \right) - s_6 \left( c_2 s_5 + c_5 \left( s_2 s_3 s_4 - c_3 c_4 s_2 \right) \right);
\]
\[
a_{33} = s_5 \left( s_2 s_3 s_4 - c_3 c_4 s_2 \right) - c_2 c_5;
\]
\[
a_{34} = l_6 \left( c_3 s_2 s_4 + c_4 s_2 s_3 \right) - l_3 s_2 - l_4 c_3 s_2 - l_5 c_3 c_4 s_2 + l_5 s_2 s_3 s_4;
\]
\[
a_{41} = 0; \quad a_{42} = 0; \quad a_{43} = 0; \quad a_{44} = 0;
\]
The rotational vector (R) and position vector (P) of the end-effector were obtained from this transformation matrix.

\[
R = \begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{bmatrix} \quad P = \begin{bmatrix}
a_{41} \\
a_{42} \\
a_{43} \\
a_{44}
\end{bmatrix}
\]

### 3.2 Workspace Analysis

A MATLAB code was implemented to determine all the reachable points of the end effector from the forward kinematics of the robotics system. The workspace of the 6-DoF arm assembly was calculated using the matrix 'P' in MATLAB.

For this, the link length of each joint and joint angle have been defined. The link lengths for the arm assembly were done subject-specific and those are as follows:

\[
l_1 = 80.2, l_2 = 211.5, l_3 = 76.3, l_4 = 232.57, l_5 = 154.4, l_6 = 127.69
\]

The \( \theta \) range for each assembly joint was done by taking into consideration human motion as follows:

- \( \theta_1 = \left( -\frac{\pi}{9} \right) \) to \( \left( \frac{7\pi}{18} \right) \)
- \( \theta_2 = \left( -\frac{\pi}{9} \right) \) to \( \left( \frac{\pi}{2} \right) \)
- \( \theta_3 = \left( -\frac{\pi}{36} \right) \) to \( \left( \frac{2\pi}{3} \right) \)
- \( \theta_4 = \left( -\frac{\pi}{36} \right) \) to \( \left( \frac{23\pi}{36} \right) \)
- \( \theta_5 = \left( -\frac{17\pi}{36} \right) \) to \( \left( \frac{\pi}{36} \right) \)
- \( \theta_6 = \left( -\frac{5\pi}{36} \right) \) to \( \left( \frac{\pi}{9} \right) \)

Utilizing the link lengths and range of angles in MATLAB code, the workspace for the arm assembly was determined.
4 Discussions

The fabrication of the exoskeleton and its ability to facilitate a wide range of arm movements with minimum restriction represents a significant achievement and shows practicality in its assistance. The versatility of the exoskeleton is evident in its ability to fit a wide range of individuals, irrespective of their physical dimensions. This adaptability is primarily attributed to modifications made in the shoulder blade assembly and back support. Testing has demonstrated the exoskeleton's ability to provide support when the arm is positioned above the horizontal level. This addresses a common challenge for individuals with weak joints, especially when lifting objects above shoulder height.

All the tests have consistently shown that the exoskeleton prototype effectively provides the necessary range of motion for both the arm and fingers. The specially designed fingers significantly improve the process of grasping objects, promoting better rehabilitation. Notably, the prototype is lightweight and features ample space between the fingers, ensuring user-friendliness. A single motor efficiently controls the multiple finger joints, resulting in a strong grip while minimizing space requirements. The arms offer support at higher angles and enable lifting objects with ease. These joints enable a complete range of motion and proficiently distribute the load. The exoskeleton has proven to be beneficial for individuals with weaker joints and also for industrial workers.

The potential for this exoskeleton to be used in industrial settings, particularly for load handling, holds promise. To facilitate its industrial use, careful consideration should be given to manufacturing structural components according to the expected load-bearing requirements, as well as configuring motors appropriately. The exoskeleton has successfully achieved its goal of assisting patients with finger mobility disorders.
5 Conclusion

The exoskeleton effectively provides a full range of motion for both arms and fingers along with a lightweight, user-friendly environment resulting in improved rehabilitation. Hence, the exoskeleton's design and testing have demonstrated promising results regarding mobility, adaptability, and practical application. Its potential to address challenges in both medical and industrial settings suggests a bright future for this technology. Additional research and refinement, alongside professional input, will further enhance its clinical and real-world utility. A thorough evaluation of clinical benefits will ensure a connection with the unique needs of patients and proactively identify potential complications, which will help in the potential growth of the exoskeleton assistance.

References