A Novel Shoulder Mechanism with a Double Parallelogram Linkage for Upper-Body Exoskeletons

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***Abstract*— The design of an innovative spherical mechanism with three degrees of freedom for a shoulder joint exoskeleton is presented in this paper. The spherical mechanism is designed with a double parallelogram linkage, which connects two revolute joints to implement the motion as a spherical joint, while maintaining the remote center of rotation. The design has several new features compared to the current state-of-the-art: (1) a relative large range of motion free of singularity, (2) high overall stiffness, (3) lightweight and (4) compact, which make it suitable for assistive exoskeletons.**

I. Introduction

Traditional designs of shoulder exoskeletons use an serial linkage system with 3-revolute (3R) joints [1], [2] to generate the spherical motion of the human shoulder joint. A problem with a serial structure is its workspace limit. The user of the exoskeleton can only raise the upper arm a small angle in the frontal plane before the shoulder mechanism collides with his/hers shoulder, neck or head. To avoid this problem, some alternative designs have been proposed. The designs in [1], [2] minimized the effect of these problems by designing their exoskeletons so that the singular configurations and collision problem of the 3R mechanism occur at postures that are less likely for the user to reach. In another approach, reported in [3], one of the links in the 3R mechanism is replaced with a circular guide to further avoid collision with the user.

In this paper a novel spherical mechanism using double parallelogram linkages (DPM in short) is presented. The mechanism is featured with a compact structure, lightweight yet rigid design, and a large range of motion free of singularity. The proposed mechanism is to be used as a novel glenohumeral joint mechanism for an upper-body exoskeleton.

II. Conceptual design of novel shoulder mechanism for an upper-body exoskeleton

The proposed design consists of two revolute joints that are connected together via four links, as shown in Fig. 1. The four links form a double parallelogram mechanism (DPM), which under the given configuration form a remote center of motion mechanism [4]. The revolute joints produce extension/flexion and abduction/adduction respectively, while the DPM produces the internal/external rotation. The working principle is similar to the 3R mechanisms, meaning it can rotate about three independent axes that all coincide in one point, namely, the Remote Center (RC) (see Fig. 1).

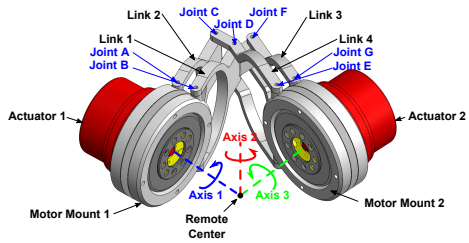

Fig. 1. Design concept of the Double Parallelogram Mechanism.

The proposed design is constructed as a hybrid mechanism. The benefit of the proposed design is that the chance of collision with the user is minimized compared to the classical 3R mechanism having two links in series. Moreover, the structure is more compact, lighter and less complicated compared to the 3R mechanism using a circular guide.

The design parameters of the DPM are displayed in Fig. 2, which include four link lengths and two offset angles. The links L_1 and L_2 are the lengths of the first parallelogram and L_3 and L_4 are the lengths of the second parallelogram. For the proposed design, the offset angles are introduced mainly to account for the footprint of the actuators, where ϕ_2 accounts for the actuator at θ_1 and ϕ_1 for the actuator at θ_3. The range of motion of the DPM, i.e. θ_2, is limited by the footprint of the two revolute joints and the collision with the human shoulder. Axis of joint 1 is aligned with $\mathcal{L}_1$, while axis of joint 3 is aligned with $\mathcal{L}_2$.

III. Kinematic analysis of the mechanism

The kinematics of the proposed mechanism is formulated based on Denavit-Hartenbergs convention. Cartesian coordinate frames are attached to each link of a manipulator, as shown in Figure 2. The corresponding DH parameters can be obtained as listed in Table I. Using these parameters the rotation matrix is obtained as:

$$\mathbf{R} = \begin{bmatrix} c\theta_1 c\theta_2 c\theta_3 - s\theta_1 s\theta_3 & -c\theta_3 s\theta_1 - c\theta_1 c\theta_2 s\theta_3 & -c\theta_1 s\theta_2 \\ c\theta_1 s\theta_3 + c\theta_2 c\theta_3 s\theta_1 & c\theta_1 c\theta_3 - c\theta_2 s\theta_1 s\theta_3 & -s\theta_1 s\theta_2 \\ c\theta_3 s\theta_2 & -s\theta_2 s\theta_3 & c\theta_2 \end{bmatrix} \quad (1)$$

where θ_1, θ_2 and θ_3 are the joint angles. Also, c and s stands for cos and sin respectively.

The work reported here is supported by the EU AAL Programme and Innovation Fund Denmark.

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TABLE I

DENAVIT-HARTENBERG PARAMETERS OF THE PROPOSED MECHANISM.

Link, i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	$L_3 \sin\phi_2$	-90°	0	90° + ϕ_1 - θ_2
3	L_2	0	0	180° - ϕ_1 - ϕ_2 + θ_2
4	L_3	0	0	90° + ϕ_2 - θ_2
5	$L_2 \sin\phi_1$	90°	0	θ_3

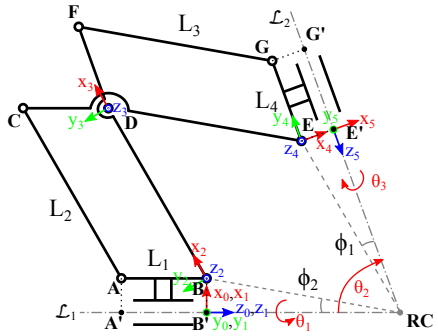

Fig. 2. Coordinate frames attached to the links of the Shoulder Mechanism

The inverse kinematics problem is solved for the three joint angles:

$$\begin{aligned}\theta_2 &= \arccos(r_{33})\\ \theta_1 &= \arctan 2\left(-r_{23}/s\theta_2, -r_{13}/s\theta_2\right)\\ \theta_3 &= \arctan 2\left(-r_{32}/s\theta_2, r_{31}/s\theta_2\right)\end{aligned}$$

where $r_{i,j}$ stands for the (i,j)th element of the matrix $\mathbf{R}$. It should be noted that there are two possible solutions for θ_2, but given the allowable range of motion only the solution between 0 and 180° is used.

The velocity and singularity analysis of the DPM can be performed by deriving the Jacobian for the angular velocities:

$$\dot{\theta} = \mathbf{J}_\omega{}^{-1}\omega_\mathbf{e} \tag{2}$$

where $\dot{\theta} = \begin{bmatrix}\dot{\theta}_1 & \dot{\theta}_2 & \dot{\theta}_3\end{bmatrix}^T$ is a vector with the joint angular velocities, $\mathbf{J}_\omega$ is the Jacobian and $\omega_\mathbf{e} = \begin{bmatrix}\omega_x & \omega_y & \omega_z\end{bmatrix}^T$ is the end-effector angular velocities. The Jacobian is found as:

$$\mathbf{J}_\omega = \begin{bmatrix} 0 & s\theta_1 & -c\theta_1 s\theta_2 \\ 0 & -c\theta_1 & -s\theta_1 s\theta_2 \\ 1 & 0 & c\theta_2 \end{bmatrix} \tag{3}$$

A common measure of the evaluating the performance of a mechanism is the manipulability index μ, which is defined as:

$$\mu(\mathbf{J}) = \sqrt{\left|\mathbf{J}\mathbf{J}^T\right|} = |s\theta_2| \tag{4}$$

From Eq. (4) it is clear that the kinematic performance of the DPM only depends on the angle of the double parallelogram. The manipulability index over the range of motion of the parallelogram is shown in Fig. 3, where it is seen that the DPM is at a singular configuration in the case that the joint axes constitute a common plane ($\theta_2 = 0, \pi$). Due to the two offset angles, the proposed design has a minimum angle of $\theta_{2,min} = \phi_1 + \phi_2$. Thus, the singular configuration of $\theta_2 = 0$, is not obtainable. According to [2], a range of motion for shoulder internal/external rotation of 135° is sufficient for most of our activities of daily living. Hence, the mechanism is free of singularities and covers the required range of motion if the maximum angle satisfies the following condition $\theta_{2,max} = \theta_{2,min} + 135° < 180°$.

IV. APPLICATION OF THE NOVEL SPHERICAL SHOULDER MECHANISM

The application of the novel shoulder mechanism in an exoskeleton design is illustrated in Fig. 4. The exoskeleton is intended as a part of a portable exoskeleton for elderly to assist them in their daily activities. For the proposed exoskeleton design, the two revolute joints are actuated by a Flat DC motor (EC60 from maxon motors) and a Harmonic Drive Gear (CSD-25-2A from Harmonic Drive) each, while the DPM is left passive. As seen from the figure, the novel shoulder mechanism has a compact design without compromising the range of motion.

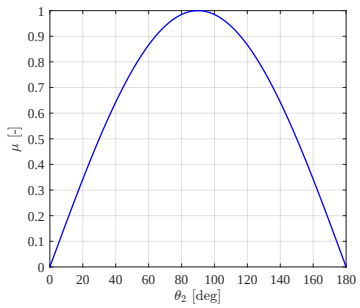

Fig. 3. The manipulability index of the DPM within its operation range.

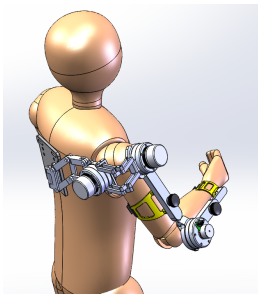

Fig. 4. The novel spherical shoulder mechanism utilized in an upper-body exoskeleton

V. CONCLUSION

In this paper, a novel spherical mechanism using a double parallelogram linkage and two revolute joints for upper-body exoskeletons has been presented. The design has several new features compared to the current state-of-the-art, such as a relative large range of motion free of singularity, high overall stiffness, lightweight and compact. As a result, the design is well suited for portable exoskeletons. A prototype of the novel design is being developed for design validation and experiments.

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