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Effects of the Link Lengths in the Design and Optimization of A 6 DOF Assistive Robot for Activities of Daily Living

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Abstract - Patients with upper and lower extremity dysfunction suffer from a non-independent life. They depend on other people to do their daily activities. Hence, the importance of assistive robots in their lives and the design challenges of these robots. The assistive robots must be capable of reaching and handling different spaces and objects. Thus, the understanding of the effects of the link lengths on the performance of the robot is a critical step in the design process. In this research, the effect of the link length of a 6 DOF serial robot applied to assistance studied. Firstly, it presents a description of the robot, from the DH parameters to the dynamic model. Later, the description of the desired workspace is observed. Finally, the study of a set of link lengths, their reachable area, and required energy consumption is discussed.

Keywords**:** Assistive Robot, Robot's Design, Optimization, Kinematics and Dynamics, Workspace, Activities of Daily Living (ADL)

1. Introduction

Individuals with dysfunctions in the upper and lower extremities depend on other persons to live. This situation generates frustration in these individuals. Hence, they consent to use robotic or electronic devices to recover independence. One of the robotics solutions for this problem is an assistive robot. These robots assist the user in the activities of daily living, such as opening doors, manipulating objects, and helping in self-care. However, it exists challenges to overcome in the design of assistive robots. It can be highlighted the constraints of size and power consumption as design challenges. Because these devices need to be transported to multiple places, and some of them could have limited power sources.

The optimization of the link lengths in an Assistive robotic arm is of great concern because of the restrictions that they constantly face regarding size, weight, required speeds, and workspace area in the fields like social interaction, tomography, construction, surgery [1-3]. Authors considered the maximum workspace area and the local indices (prismatic or rotational joint) in [4]. Still, their analysis was for a DOF robot only, which concluded that the design would be better with more revolute joints. The design criteria of the link lengths for a 7 DOF robot is computed using a genetic algorithm to optimize the size of the workspace, the agility, and the energetic efficiency of the robot arm in [5]. A different optimization approach is taken in [6, 7] that works for both parallel and linear robots that want to optimize stiffness and minimize the structure's overall weight. In [8] task-based times and the average joint torques for both planar and spatial 3 DOF robots are considered for optimization. In [9] the authors perform a reliability analysis and optimization by understanding and avoiding uncertainties in the operational points defined as most Probable Point of Failure. In [10] another 7DOF robot performs a multi-parameter optimization, including the global conditioning and structural length indices following the Taguchi Method, Grey relational Analysis and Analysis of Variance (ANOVA) to determine the overall impact of the link assignment. In [11] a non-gradient optimization method is considered which is a complex method, to evaluate multiple designs within a feasible domain and find the best and worst configurations. An integrated design optimization is performed in [12] where robot kinematics, dynamics, drive-train design, and strength analysis are considered in lights of finite elements analysis to minimize the robot's weight. The genetic algorithm (GA) is used in [13] for the mechanical design (link length, diameter, and thickness) optimization of a 6DOF robot for specific tasks like automated cleaning or fish processing tanks. In [1] a new hybrid functions of GA pattern search (PS) and fmincon (Matlab nonlinear solver) is proposed to optimize the link lengths of 3, 6, and 9DOF robot arms for computed tomography. Recent studies consider Differential Evolution (DE) with local search to determine the joint configuration and link length of a 6DOF robot [14, 15].

This paper presents an analysis of the effects of the link lengths on the performance of an assistive robot. The robot will perform assistance in the activities of daily living for individuals with limited movement. Furthermore, the analysis includes the definition of a kinematic index. This index aims to measure the required static torque within the workspace. Additionally, the desired workspaces are established to fulfil the essential ADLs.

The remining structure of this study contains the description of the assistive robotic arm to be optimized in Section 2, then a breakdown of the kinematics and kinetics performance index (GSTI) and the objective workspaces (ADL) used to measure the effectiveness of the optimization in Section 3 and 4. Then in Section 5, the results present the obtained lengths, workspace coverage percentages and GSTI values for each one of the links which are discussed to ultimately transition into the final parameters with performance metrics to build a 6 DOF assistive robotic arm for activities of the daily living.

2. Description of the Proposed Assistive Robot

The analysed assistive robot is a serial robot with six revolute joints. The configuration of the robot follows the Denavit Hartenberg (DH) parameters[16] shown in table 1. These parameters follow the homogeneous transformation matrix (HTM) convention presented below.

$$^{i-1}T_i = \begin{bmatrix} 1 & 0 & 0 & a_{i-i} \\ 0 & \cos\alpha_{i-i} & -\sin\alpha_{i-i} & 0 \\ 0 & \sin\alpha_{i-i} & \cos\alpha_{i-i} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Table 1: DH Parameters of the Proposed Assistive Robot.

	a_{i-1}	α_{i-1}	d_i	θ_i
Joint 1	0	0	L_1	θ_1
Joint 2	0	$\pi/2$	0	$\theta_2+\pi/2$
Joint 3	L_2	0	0	$\theta_3-\pi/2$
Joint 4	0	$-\pi/2$	L_3+L_4	θ_4
Joint 5	0	$\pi/2$	0	θ_5
Joint 6	0	$-\pi/2$	L_5+L_6	θ_6

Where α_i and a_i represent the link twist and length, respectively; θ_i and d_i describe the joint variable of revolute joint and link offset, respectively.

The dynamic model of the proposed assistive robot is described by Eq. (2). This dynamic model shows the correlation between the external forces/torques over the robot and the actuator's torque. Hence, the model considers the mass and inertia of each link, represented by $M \in R^{6\times 6}$; the Coriolis and centrifugal effects, $C \in \boldsymbol{R^{6\times 6}}$; and the effects of the gravity, $G \in \boldsymbol{R^6}$.

$$\tau = M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) \tag{2}$$

However, the inertial effects are ignored by this study because they are more related to the robot motion than the link length configuration. Thus, Eq. (3) represents the static torque of the robot.

$$\boldsymbol{\tau} = G(\theta) \tag{3}$$

3. Global Square Torque Index (GSTI)

The mechanical design has a critical impact on the kinematic and kinetic performance of a robotic device. Hence, many researchers have been working on studies about performance indexes to evaluate the kinematic of a robot. Between these studies, there are some indexes considered classical such as the condition number [17], the manipulability index [18], and the velocity index [19]. Moreover, these indexes have received improvements from new studies in recent years [20-22].

This study presents an index inspired by Boscariol et al. [23]. This index aims to measure the required static torque by the robot within the workspace. Then, the index takes the static torque described by Eq. (4) and applies the dot product to get the square sum of the torque in a specific pose of the robot. The index is as follows.

$$\boldsymbol{GSTI} = \eta \int_{W} \mathrm{G}(\theta) \cdot G(\theta) dW \tag{4}$$

Where $(\cdot)$ W symbolizes the workspace to compute the index; η is a penalty coefficient described by Eq. 5; $(\cdot)$ denotes the dot product.

$$\eta = \frac{W}{W_{reachable}} \tag{5}$$

Note the index can be interpreted as the energy consumption of the robot. Hence, if the GSTI decreases, it represents a decrease in the energy consumption and the required torque to manipulate the weight of the end-effector.

4. Workspace for Activities of Daily Living

The patients with upper and lower extremities dysfunctions want to live with autonomy. They are motived to use of robotic devices to accomplish their Activities of Daily Living such as personal hygiene, eating, and manipulating objects [24, 25]. Due to this, the assistive robots must be capable of reaching and handling articles from different places. These places could be the ground, a table, or the upper part of a shelf. Thus, it was established three relevant workspaces that the robot must reach, see Fig. 1.

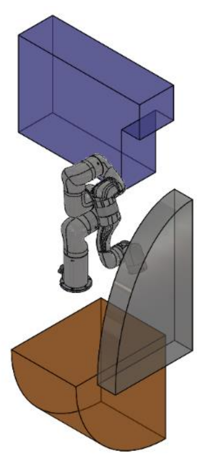

Fig. 1: Required Workspace for the Activities of Daily Living.

These three workspaces represent the required workspace to do the activities. The purple workspace, called workspace A, is related to actions like holding and manoeuvring things near the patient. The Gray workspace, workspace B, is far from the patient and activities with a desk table or upper shelf. The brown workspace, workspace C, relates activities such as picking objects from the ground. The boundaries for each workspace are shown in Table 2.

Table 2: Boundaries of the workspaces

	$X_{(min)}$ (mm)	$X_{(max)}$ (mm)	$Y_{(min)}$ (mm)	$Y_{(max)}$ (mm)	$Z_{(min)}$ (mm)	$Z_{(max)}$ (mm)
Workspace A	-460	0	0	470	330	800
	$X_{(min)}$ (mm)	$X_{(max)}$ (mm)	$R_{(min)}$ (mm)	$R_{(max)}$ (mm)	$\theta_{(min)}$ (deg)	$\theta_{(max)}$ (deg)
Workspace B	550	650	0	430	90	0
Workspace C	140	500	0	500	-180	-90

5. Results and Discussion

This section analyses the effects of the link lengths in the design and optimization of the 6 DOF proposed assistive robot. First, a set of robot configurations are presented in Table 3. These configurations have link length values randomly generated between 100 mm and 500 mm. Second, the workspaces to analyse are described in Table 2. These workspaces are discretized in 64000 even separated points to simplify the analysis. Third, at each pose of the workspace is computed the inverse kinematic, also the static torque. Finally, the reachable workspace and the GSTI are estimated.

Table 3: Utilized link lengths.

i	L_1 (mm)	L_2 (mm)	L_3 (mm)	L_4 (mm)	L_5 (mm)	L_6 (mm)
1	234.21	150.34	266.67	230.21	204.51	157.18
2	206.84	411.05	164.37	188.76	132.53	156.50
3	200.20	412.41	166.08	199.71	130.00	150.00
4	425.89	465.35	211.40	485.96	482.87	156.75
5	462.32	352.94	318.75	163.05	294.15	268.70
6	150.79	139.02	483.00	488.24	420.11	466.29

As it is shown in Table 4, neither of the robot configurations can reach the desired workspace. All of them have problems with workspace B and C. If it is analysed the robots with the most coverage, their higher link lengths are the L_2, $L3$, and L_4. This observation can be explained because these three links have a relevant meaning on the end-effector's position; see the inverse kinematic. Furthermore, if the three last link lengths are small, that reduces the required static torque.

Table 4: Reachable workspace and GSTI

i	Sum of link lengths (mm)	Reachable Workspace A (%)	Reachable Workspace B (%)	Reachable Workspace C (%)	$GSTI$ $(Nm)^2$
1	1243.12	54.56	26.16	0.00	5.66E+08
2	1260.05	98.66	69.50	60.54	7.16E+07
3	1258.40	98.94	74.85	70.17	6.30E+07
4	2228.22	73.78	74.88	97.68	1.07E+08
5	1859.91	95.57	10.09	1.79	2.51E+08
6	2147.46	30.27	38.31	20.25	1.95E+09

Now, analysing in detail the case of the robot configurations 3 and 4, see Fig. 2, it can be observed that more link length does not represent more workspace coverage. Even, it can imply the existence of non-reachable regions within the workspace. Likewise, it causes a considerable increment in the required energy during the robot motion.

a) b)

Fig. 2: Required Workspace for the Activities of Daily Living.

6. Conclusion

In this research, the effects of the link lengths in assistive robots were studied. The proposed assistive robot to analyse is a 6 DOF serial robot. This robot follows the DH parameters described in Table 1 and Eq. (1). A set of link lengths were randomly generated. From these configurations, it was observed the influence of the first links in the end-effector's position. Likewise, it was found higher lengths do not guarantee a more covered workspace and best performance. Due to it can produce the existence of non-reachable regions and heavy links. Thus, future studies will explore optimization methods to set the link lengths that ensure assistance in the activities for people with upper extremities dysfunctions.

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