Design and Optimization of 4-Degree-of-Freedom Anthropomorphic Robotic Manipulator

Abhinav Sharma, S. C. Rishabh Bavithran, and Pritish Shubham

Abstract Robotic manipulator is an automated arm widely used for manipulating objects without or minimal human intervention. Maximizing the power efficiency and the dexterous workspace is invariably a primary factor in designing an industrial robot arm. The manipulator structure is an arrangement of joints and links to form a kinematic chain which plays a vital role in deciding the arm's characteristics and overall performance. In this paper, the designing and optimizing of the manipulator structure, workflow of an articulated industrial robot, and its kinematics using D-H convention are presented. The 3D printing technique was considered for structural development, thus DfAM principles were considered for design. The outcome of the work shows the torque requirement, and overall structural weight was reduced by 15 and 20%, respectively, whereas the dexterous space improved by 18% with the proposed design of the robotic arm.

Keywords Anthropomorphic robotic manipulator · Topological optimization · Multi-body simulation · Design for additive manufacturing (DfAM)

1 Introduction

The manipulation refers to handle or control of the physical objects, thus robotic manipulators are automated machines which are used for handling and managing the desired objects autonomously without much human intervention. The robotic manipulator is based on the concept of hard robotics that deals with the use of rigid bodies whose degree of freedom is an exact measurable value.

An industrial robotic manipulator comprises of a number of rigid links and joints arranged in a certain fashion allowing them to move to interact with the surroundings. The interaction mainly depends on the constraints placed by the degree of freedom of the structure, link length and material, and power of actuation. The actuation is mostly provided by servo motors or stepper motors.

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A manipulator is required to work for many hours continuously and it has high power consumptions. An efficient robot with minimized power consumption and the improved dexterous workspace is always desired. These characteristics could be achieved with an optimal design of manipulator structure and joint design. Regardless of the link arrangement, the design itself will reduce the overall torque requirement and increase power efficiency significantly which is beneficial regardless of any type of motor used for actuation.

Several types of researches had been carried out to increase the efficiency of the robot and reduce the torque requirement. A study by Mustafa et al. [1] found out the ways to reduce the redundant weight of the robot by optimizing some existing popular robot. Another study by Sahu and Chaudhary et al. [2] shows that the load-carrying capacity, the relation between geometric variations and various materials used to make the link play a major role in determining the overall efficiency. Zhou et al. [3] studied the effect of design changes to improve the robot's payload. Similar outcomes were reported by other researchers too which shows relation between the structural arrangement of links and torque requirement [4–9].

Majority of research in this field focuses on the link arrangement and its connection. Very few papers were found which worked on the optimizing the design of the link. And negligible research focused on topological optimization of link structure and the DFMA for the joint connection configuration using 3D printing technique. Therefore, a novel approach for the designing the optimized structure and the innovative joint configuration design for improving the performance of the manipulator was undertaken in this research work. This paper discusses the complete workflow that goes into the design of a robotic manipulator including the motion simulation and stress analysis.

2 Design Methodology

2.1 Design Considerations

Joint Consideration The type of joints provided in the robot certainly determines the type of workspace that will be enveloped. All prismatic joints in a robot will provide a cuboidal workspace with a limited degree of freedom which means that there is not much freedom in selecting the end-effector orientation approach. The articulated robot that is the most popular in the industrial sector has rotary joints. The degree of freedom for this robot is high with a spherical workspace. Different combinations of prismatic and rotary joints even their sequence can alter the workspace drastically. The anthropomorphic configuration of robotic manipulator was considered for design and optimization.

Degree of Freedom The degree of freedom in a robot is the number of individual parameters or variables that are required to determine the position of the end effector. The DOF of a robot can be found using the Formula as presented in Eq. 1 [10].

$$\text{Degree of freedom} = m(N - 1 - J) + \sum_{i=1}^{J} f_i \tag{1}$$

$N =$ number of links, including ground; $J =$ number of joints
$m =$ degrees of freedom of a single body ($m = 6$ for spatial and 3 for planar body)
$f_i =$ the degree of freedom of joint number 'i'.

Design for Additive Manufacturing (DfAM) The DfAM is a technique which is used in correlation with 3D printing process. DfAM helps to increase the efficiency and flexibility of design and the parts designed through DfAM save a considerable amount of material, cost, and time. For the present work, DfAM technique was used for optimized design of link structure and the gear train for the joint configuration.

Link Design. The dimensions of each link and their order determine the reach of the workspace and the torque required to move the links. Improper link length and arrangement can cause high unnecessary power loss, increased weight of the overall design, and imbalanced center of gravity. The link dimensions and arrangement should be as such that maximum dexterous workspace is obtained along with maximum power efficiency. The generic cylindrical shape was considered as the base for link design and further topological optimization was performed using the Altair Inspire software for improving the performance of the manipulator.

Gear Design. Motion from one link to another is transmitted through actuator system that is positioned at the joint. The electrical actuation system using stepper motors was considered for the present. Stepper motors with high torque transmission capability are bulky and difficult to include in the considered robot design. Therefore, the torque provided by the average stepper motors, if used, needs to be enhanced by some mechanism—thus gear train was considered in the joint configuration. The torque requirement for each joint was obtained by using the multi-body simulation analysis. For configuring the joints and connection between the links—epicyclic gear arrangement was found to be the best solution. This is attributed to its compactness and large speed variation capability. The DfAM technique was used for creating the epicyclic gear train embedded within the link structure for creating the joint configuration. This resulted in improving the torque transmission capability of the motor to the connecting link.

2.2 CAD

The computer-aided design (CAD) is used for creating virtual model of the conceptualized part. CREO parametric software was extensively used for designing and assembly of the components of the manipulator. CREO allows 3D direct modeling, 2D orthographic views, and simulation using various mechanisms for testing the assembly.

For multi-body simulation and topographical optimization, Altair Inspire software was considered due to the ease of workflow and high accuracy achievability. The motion analysis helps in observing the variation in motion a through intricate contacts between the joints and link and troubleshoot them if needed. Added to this, Inspire simulation predicts the power required to obtain the motion which greatly varies with a lot of variables that can be set within the software itself to mimic the real-life working conditions and obtain the most accurate theoretical results.

2.3 3D Printing

The 3D printing (3D-P) is a layered fabrication process which is a subdomain of additive manufacturing. It is majorly used for rapid prototyping processes. The main advantage of 3D-P process is its ability to directly convert the digital CAD design to a real product without much need of human intervention. For the present work, FDM 3D-P was used for developing the prototype of the robotic manipulator for design validation. Ultimate Cura software was used for simulating the 3D-P process and optimizing the print time and material requirement without compromising the strength.

3 Results and Discussion

3.1 Link Design

The manipulator design was created with joint configurations and assembled by using 'CREO Parametric' software. Multi-body motion simulation was performed on the designed assembly using Altair Inspire. Based on these simulation results, improvements were made which cumulatively add up to the final design. With different iterations made to the design, reduction in the torque requirement of motors and weight of the links were considered for enhancing the manipulator performance. Figure 1 shows the different design iteration layout along with their workspace envelop. The links were arranged in such a manner that every link can move without any hindrance with the system and surrounding links.

The DeIt-01, the 1st Design Iteration, shown in Fig. 1 was initially developed for high reach capability. But it has issues of non-reachability to the tablespace for picking the object, as well as the dexterous workspace obtained was also minimal with very high torque requirements. Taking cues from the flaws of the first design, alterations were made to the link lengths and the arrangement and developed DeIt-02. The design iteration DeIt-02 requires lower torque, as well as the reachability of the robot had increased by 20%. Both DeIt-01 and 02 have 3 degrees of freedom as the end-effector link was rigid and fixed with link 3 (Figs. 2, 3).

To increase the dexterous workspace, another degree of freedom was added to the manipulator in design iteration DeIt-03 which has 1 DOF for orientation of

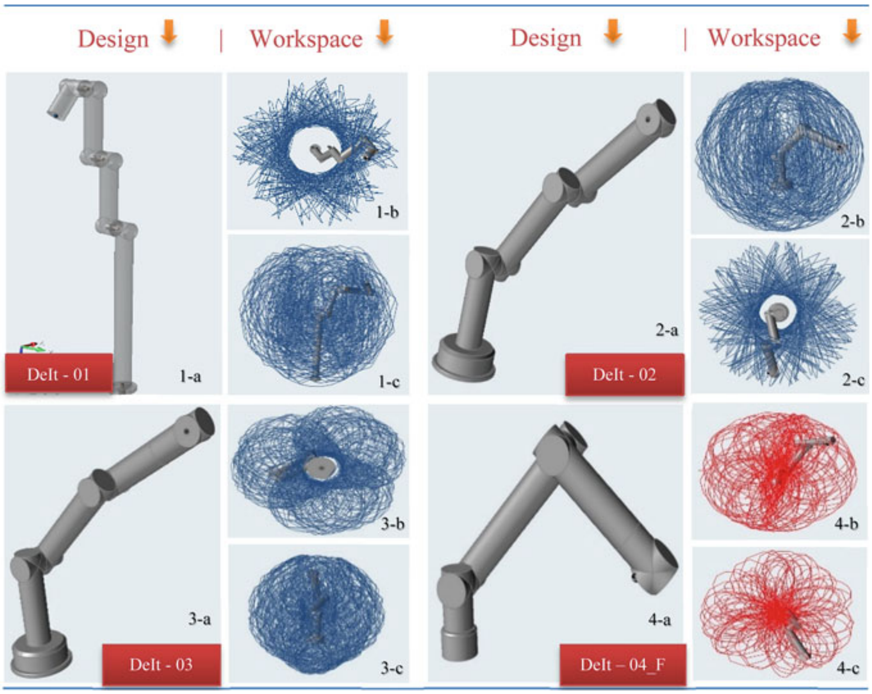

Fig. 1 Design iterations [DeIt 1–4]: **a** link configuration, **b** and **c** workspace envelop

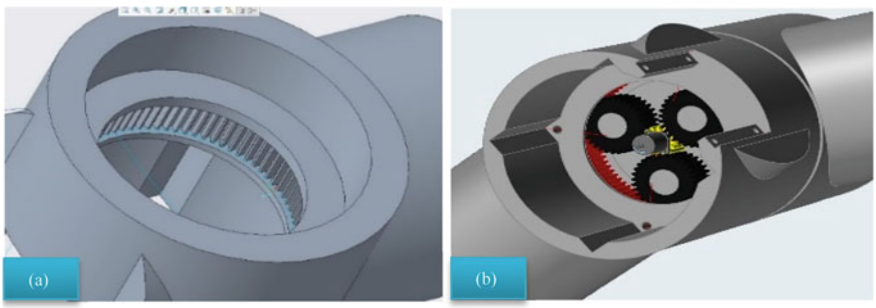

Fig. 2 Joint configuration: **a** ring gear design using DfAM technique and **b** assembly of inbuilt epicyclic gear train inside link

the end effector and 3 for the position. This enhances the Dexterous workspace by 10% as shown in Figs. 1, 3b and c. This final design iteration, DeIt-04_F, minor alterations with lengths, resulted in required torque minimized drastically and the Dexterous workspace further increased by 10%. The DOF for DeIt-03 and 04 was considered to be 4. Table 1 shows the improvement in power efficiency by considering

Fig. 3 D-H convention frame layout

Table 1 Increased power efficiency with each iteration

Motor	Percentage reduction with each design iteration			
	DeIt-01 (%)	DeIt-02 (%)	DeIt-03 (%)	DeIt-04 (%)
Base motor	–	−46	23	42
First link motor	–	0	0	34
Second link motor	–	−37	43	−22
E-E orientation motor	–	–	–	50

the previous iteration as the reference for computation in change percentage of the power requirement.

3.2 *Joint Configuration Design*

Designing planetary gear set for the joints and incorporating them in the link design itself contributed to the aesthetics and significant reduction in the overall weight. Yang Cao's et al. [11] methods were used to design all gears in CAD software. The planetary gear set was designed in such a way that the motor drives the sun gear and the power output is drawn from the planet gears and transmitted to the adjacent link to create movement. Equation 2 represents the speed ratio, from which it can be observed that by increasing the number of teeth on the ring gear and keeping the number of teeth on sun gear as low as possible, a high gear ratio can be attained which in turn results in less torque requirements.

$$\frac{\omega_s}{\omega_c} = 1 + \frac{z_r}{z_s} \tag{2}$$

By including self-designed planetary gear set in the joints, the power of the motor is best utilized. The use of gears reduces the torque requirement of the motor and further reduces the weight of the motor to be used. This makes the manipulator much efficient. For designing the ring gear, it is considered that the diameter of the link is not to be exceeding 100 mm. The joint must be configured within this limit including and for that, the pitch circle diameter of the ring gear was fixed at 80 mm. Thus, the number of teeth on the ring gear will also be 80 for keeping the modulus same. For the sun gear design, to avoiding any size and strength constraints, the pitch circle diameter of the sun gear was computed as 16 mm. As the diametral pitch is kept 1, the number of teeth on the sun gear will be 16. The planet gear teeth calculation (Eq. 3) was done by subtracting the radius of ring gear with the radius of the sun gear.

$$2r_p = (\mathrm{d}_r/2) - (\mathrm{d}_s/2) \tag{3}$$

$$2r_p = 40 - 8; \quad 2r_p = 32$$

To incorporate the epicyclic gear train in the joints, the design of ring gear was included within the link structure itself as shown in Fig. 2a. The planetary gears transmit the motion directly to the adjacent link and to mount them three cylindrical extrusions were made at the end of the connection. The planet gears will have the freedom to rotate around these rods with the help of bearings. Figure 2b shows the gear assembly enclosed within the manipulator link

3.3 Kinematics of Robotic Manipulator

The inverse kinematics with Denavit Hartenberg convention was considered to find the transformation matrices for determining the location of the end-effector. The frame layout along with the dimensions is shown in Fig. 3. The base as a reference is numbered as 0 and links are from 1 to 4. To determine transformation matrix ${}^{0}T_4$, which represents the positioning of link 4 with respect to base 0, Eqs. 4 and 5 were considered.

$${}^{0}T_4 \times {}^{4}P = {}^{0}P \tag{4}$$

$${}^{0}T_4 = {}^{0}T_1 \times {}^{1}T_2 \times {}^{2}T_3 \times {}^{3}T_4 \tag{5}$$

The homogeneous transformation matrix for determining the position of links can be found through the D–H convention Table 2.

The table shows the four different parameters—joint angle (θ), link twist (α), link length (r), and link distance (d) for relating the link and joint variables. Multiplying all the 4 matrices we get the transformation matrix from 0th frame to 4th frame, we

Table 2 D-H convention table for manipulator kinematics

Frame no.	θ	α	r	d
1	θ_1 (q)	90°	0	22
2	θ_2 (r)	0°	−50	10.3
3	$\theta_3(s)$	−90°	0	−10.3
4	$\theta_4(t)$	0°	0	32

get the matrix as shown in Eq. 7. The transformation matrix ${}^0T_4$ can be found using the values shown in Table 2, represented in Eq. 6:

$$\begin{bmatrix} \text{Cos}\theta_n & -\text{Sin}\theta_n\text{Cos}\alpha_n & \text{Sin}\theta_n\text{Sin}\alpha_n & r_n\text{Cos}\theta_n \\ \text{Sin}\theta_n & \text{Cos}\theta_n\text{Cos}\alpha_n & -\text{Cos}\theta_n\text{Sin}\alpha_n & r_n\text{Sin}\theta_n \\ 0 & \text{Sin}\alpha_n & \text{Cos}\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} -S(q)S(t) - S(r+s)C(q)C(t) & -S(q)C(t) + S(t)S(r+s)C(q) & -C(q)C(r+s) & -50C(q)C(r) - 32C(q)C(r+s) \\ -S(q)S(r+s)C(t) + S(t)C(q) & S(q)S(t)S(r+s) + C(q)C(t) & -S(q)C(r+s) & -50S(q)C(r) - 32S(q)C(r+s) \\ C(t)C(r+s) & -S(t)C(r+s) & -S(r+s) & -50S(r) - 32(r+s) + 22 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

Here, Sin and Cos are represented as ‘S’ and ‘C’, respectively. Using Eq. 5, any point in the end effector frame (4th frame) with any angular orientation of the joints, the same point can be found with respect to the 0th frame and vice versa. The point in the 0th frame where the end-effector is supposed to reach is denoted as x, y, and z variables. The point in the end-effector frame is taken as (0, 0, 0). On solving Eq. 5, taking only the translation part of the overall matrix, we get

$${}^0P = \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad {}^4P = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$x = -50\,\text{Cos}(q)\text{Cos}(r) - 32\,\text{Cos}(q)\,\text{Cos}(r+s)$$
$$y = -50\,\text{Sin}(q)\text{Cos}(r) - 32\,\text{Sin}(q)\,\text{Cos}(r+s)$$
$$z = -50\,\text{Sin (r)} - 32\,\text{Sin}(r+s) + 22$$

The angular variables q, r, and s decide the position of the end effector. The angular variable t is absent from all the three equations. This implies that ‘t’ does not have any impact on the position of the end-effector but the angular orientation of the end-effector.

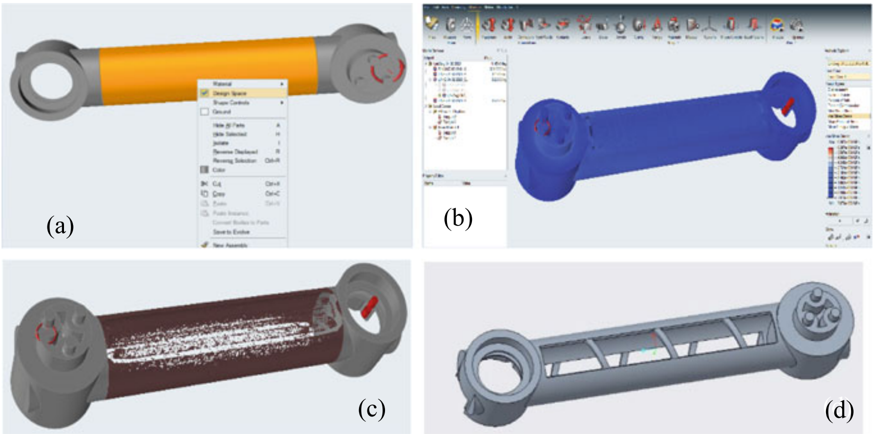

Fig. 4 Topological optimization: **a** design space of link, **b** stress analysis, **c** optimization result, and **d** final link design

3.4 Topological Optimization

Stress analysis and topological optimization of the links were done to reduce the weight of the manipulator. Various constraints were placed on the design such that it mimics the real-time working constraints. Link 3 was the largest and heaviest and hence the optimization was performed on the same. Figure 4a shows the design space consideration in link. Figure 4b and c is the outcome of the optimization, and Fig. 4d is the final design of the link after optimization with overall 20% reduced weight.

4 Conclusion

The anthropomorphic robotic manipulator was designed successfully by considering the DfAM technique for minimizing the weight and assembly of parts without compromising the strength and functionality. The topologically optimized structure reduces the overall weight by 20%. The modified epicyclic gear train arrangement and reduced weight resulted in minimizing the torque by 15%. Additionally, the modified link arrangement and its precise positioning helped to improve the dexterous workspace by 18%.

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