Optimization approaches of industrial serial manipulators to improve energy efficiency: A review

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Abstract. The objective of this paper is to provide a comprehensive review of existing approaches and techniques developed in the field of industrial robotics to make it energy efficient. The usage of industrial manipulators is increasing globally due to its superiority, repeatability, and productivity [1]. Among different methods in the field of energy-efficient robots, three approaches are focused in this paper those are topology optimization, trajectory optimization, and light-weight robotic components. In these methods, topology optimization is a promising method to distribute the material in the design space by eliminating needless densities to make the robots as more energy efficient.

1. Introduction
In the automation sector, the usage of industrial robots is increased globally due to its superiority, repeatability, and productivity [1]. Among different methods in the field of energy-efficient robots, three approaches are focused in this paper those are topology optimization, trajectory optimization, and light-weight robotic components. In these methods, topology optimization is a promising method to distribute the material in the design space by eliminating needless densities to make the robots as more energy efficient.

Topology optimization is a mathematical approach that optimizes the design space based on a given set of boundary conditions and constraints. The goal of optimization is minimizing compliance or maximizes stiffness. Topology optimization has an extensive range of applications in the field of mechanical, civil, aerospace, and robotics, etc. The review of topology optimization further classified into two groups based on loading condition, such as static and dynamic analysis. Trajectory
optimization is mainly focused on the optimal path during work cycle to minimize energy consumption. The objective of the trajectory optimization is to choose an optimal path, avoid obstacles in the work cycle, or minimization of the torque. Again the trajectory optimization categorized into two types like point-to-point optimization and multi-point optimization. The usage of light-weight components of industrial robots plays a vital role in the minimization of energy consumption. However, a significant change in the weight of robotic arms causes balancing and vibration problems and converts the rigid members into flexible members.

The paper is arranged as follows; the methodology of topology optimization is detailed, considering static and dynamic analysis in section 2. Trajectory optimization of point-to-point and multi-point methods is provided in section 3. The usage of light-weight components in the field of robotics is discussed in section 4. Finally, section 5 contains the conclusion and future scope.

2. Topology optimization

The structural optimization method is classified into three groups, such as; shape optimization, size optimization, and topology optimization. In shape optimization, the aim is to find out the optimal splines of the provided holes in the design space [2]. The goal of size optimization is to find the optimum size of a hole, which is already present in the design space. Whereas topology optimization is a powerful and emerging method for design optimization, which finds the novel connections and holes in the design space of structural components [3]. The topology optimization algorithm distributes material in design space by deleting the needless densities based on given loads and constraints. Nowadays, due to the advancement in the non-conventional machining methods such as additive manufacturing, which removes the barrier for design to manufacturing phase constraints. Due to the possibility of making any complex shape, the popularity of topology optimization methods enhanced abnormally. The objective function of the topology optimization chosen as minimum compliance and subjected to the constraints, as shown in equation (1).

\[
\min \quad C(i) = U^T KU \\
\text{Subjected to} \quad V(i) - V \times \mu = 0 \\
\quad \quad KU - P = 0 \\
\quad \quad 0 < i \leq 1
\]  

(1)

where ‘\text{i}’ is the material density variable, and ‘\text{C}’ is compliance, ‘U’ is displacement vector of design space, ‘\mu’, and ‘P’ are volume fraction and force matrix, ‘K’ is the stiffness matrix. ‘V(i)’ and ‘V’ are the volume of final material and initial design space. The design region discretized into quadrilateral four-node finite elements, as shown in Figure 1.

**Figure 1.** Node numbering scheme of the density matrix and the displacement of the element.
Here, 'NLX' and 'NLY' are the number of elements in x and y-direction, respectively. 'h_i', and 'v_i' is displacement in a horizontal and vertical direction. The total DOF in the design space is $2((NLY+1)(NLX+1))$. The length of each finite square element is 'a'. The element is subjected to a four-node bilinear displacement vector in a horizontal and vertical direction, as shown in equation (2).

$$
\begin{bmatrix}
 h_1 \\
 v_1 \\
 h_2 \\
 v_2 \\
 h_3 \\
 v_3 \\
 h_4 \\
 v_4 \\
\end{bmatrix} = \begin{bmatrix}
 2(NLY+1) y + 2 x - 2 NLY - 3 \\
 2(NLY+1) y + 2 x - 2 NLY - 2 \\
 2(NLY+1) y + 2 x - 1 \\
 2(NLY+1) y + 2 x \\
 2(NLY+1) y + 2 x + 1 \\
 2(NLY+1) y + 2 x + 2 \\
 2(NLY+1) y + 2 x - 2 NLY - 1 \\
 2(NLY+1) y + 2 x - 2 NLY \\
\end{bmatrix}
$$

(2)

The vertical and horizontal nodal deflection can be seen from the above Figure 1. Individually element is allocated to a density parameter values ($i^p$), which can be calculated using solid isotropic material with penalization (SIMP) as shown in equation (3).

$$
K_{\text{SIMP}}(i^p) = \sum_{e=1}^{N} [i_{\text{max}} + (1-i_{\text{min}})]^p_i K_e
$$

(3)

where 'K_e' is a stiffness matrix of the element. 'i_e', and 'i_{\text{min}}' are the element relative density, and minimum relative density, respectively. 'P' is the penalization (usually 3), and 'N' is an entire number of elements in the design space. The optimization problem is solved by using standard optimality criteria algorithm [4]. Similarly, different approaches are available to solve topology optimization problems like sequential linear programming (SLP), method of moving asymptotes (MMA), and sequential quadratic programming (SQP), etc. [5]. Here a heuristic updating scheme is used to update by design (density) parameters. The Lagrangian (L) for the optimization problem of objective function is written as following equation (4).

$$
L = C + \alpha_3 (V(i) - V \times f) + \alpha_1^T (KU - P) + \sum_{e=1}^{N} \alpha_3^e (i_h - i^e) + \sum_{e=1}^{N} \alpha_3^e (i^e - i_c)
$$

(4)

where 'α' is Lagrangian multiplier. 'i_h' and 'i_c' represent hole and constraint design variable. The estimation of (∂L/∂e) can achieve the optimality condition is equal to zero. A numerical parameter 'ψ' is introduced to restrict the sizeable incremental value of the design variable. The iteration scheme shown in equation (5) is used to update the design variable.

$$
\begin{align*}
 i_{h+1}^e &= \max(i_h^e, i_c^e - \psi) \quad \text{if} \quad i_h^e (O_{\psi}^e)^\top \leq \max(i_h^e, i_c^e - \psi) \\
 i_{c+1}^e &= \min(i_h^e, i_c^e + \psi) \quad \text{if} \quad i_h^e (O_{\psi}^e)^\top \geq \min(i_h^e, i_c^e + \psi) \\
 i_{h+1}^e &= i_h^e (O_{\psi}^e)^\top \quad \text{otherwise}
\end{align*}
$$

(5)

$$
\alpha_3^e = \frac{-\frac{\partial \psi}{\partial i_h}}{\frac{\partial \psi}{\partial i_c}}
$$

(6)
where \( \tau \) is the numerical damping coefficient (kept as 0.5) to steady the iteration process, and \( O_k \) acquired from optimality condition as shown in equation (6). A bisection algorithm is used to obtain the values of a Lagrangian multiplier. The iteration process is terminated once the compliance values are found to be converged. The topology optimization method is recently implemented to industrial manipulators to improve dynamic performance and energy efficiency. Majorly, the study of topology optimization is categorized into two groups, such as static analysis and dynamic analysis, which are detailed in the next subsection.

2.1. Static analysis
The implementation of topology optimization in the field of robotics was started in early 2000. Albers et al. optimized a few components of the ARMAR III humanoid topologically at static loading conditions [6]. Further, walking humanoid robot was optimized topologically using Optistruct commercial software considering multi-body static simulations [7], [8]. The researchers examined the robot at a maximum stretching position or worst condition to study the topology optimization at static loading [9-12, 18, 20]. Briot et al. optimized the industrial robot of five bar mechanism topologically considering static loads. The goal of the work is to minimize the computational time of the MATLAB code [15]. Xin et al. compared the results of size and topology optimization of industrial manipulators at maximum stretching position considering static loading conditions [16]. Liu et al. optimized the upper limb of a rehabilitation robot using Optistruct software for static analysis [17]. The high-speed flexible robot arm was investigated at static loading using the method of moving asymptotes [19]. Recently, ribs of mechanical components were optimized at different shapes such as elliptical, trapezoidal, and rectangular for different volume fractions starting from 0.1 to 0.7 [21]. The manipulator-link was considered at a horizontal position and subjected to the static force of magnitude 10 N at one end of the arm. Table 1 shows the static analysis of topology optimization.

| Author          | Year | Document type | DOF | Robot Type | Reduction | Application |
|-----------------|------|---------------|-----|------------|-----------|-------------|
| Albers et al. [6] | 2006 | Journal       | 21  | Humanoid   | Mass: 2.7 kg | Dishwasher |
| Lohmeier et al. [7] | 2006 | Journal       | 22  | Humanoid   | Torque: 35%  | Walking    |
| Lohmeier et al. [8] | 2009 | Conference    | 25  | Humanoid   | Torque: 35%  | Walking    |
| Hagenah et al. [9] | 2013 | Conference    | 6   | Manipulator | Mass: 4.9 kg | Pick and Place |
| Chen et al. [10] | 2017 | Conference    | 3   | Manipulator | Mass: 26%   | Industrial |
| Denkena et al. [11] | 2017 | Conference    | 6   | Manipulator | Mass: 5%    | Industrial |
| Zhang et al. [12] | 2017 | Journal       | 3   | Manipulator | Mass: 3.7%  | Industrial |
| Meng et al. [13] | 2017 | Conference    | 1   | Parallel Robot | Volume: 30% | - |
| Li et al. [14] | 2018 | Conference    | 6   | Manipulator | -           | Pick and Place |
| Briot et al. [15] | 2018 | Journal       | 5   | Robotic Arm | Time        | - |
| Xin et al. [16] | 2019 | Conference    | 6   | Manipulator | Weight: 26.5% | Industrial |
| Liu et al. [17] | 2019 | Conference    | 1   | Robotic Arm | Mass: 38.7% | Industrial |
| Bugday et al. [18] | 2019 | Journal       | 6   | Manipulator | Weight: 10% | Industrial |
| Alkalla et al. [19] | 2019 | Journal       | 1   | Flexible Arm | Mass: 74% | - |
| Sundar et al. [20] | 2019 | Conference    | 5   | Manipulator | -           | Industrial |
| Srinivas et al. [21] | 2020 | Conference    | 1   | Robotic Arm | Volume: 70% | Industrial |

2.2. Dynamic analysis
For better design consideration of manipulator-link dynamic loading is a must. Because topology of manipulator-link is more sensitive about the direction of the force. When robotic arm rotates about the shaft, the direction of force is in dynamic nature. Albers et al. analyzed 1-DOF humanoid link topologically using TOSCA software [22 - 24]. Multibody dynamics simulations were performed using ADAMS software to capture the dynamic loading values. Yunfei et al. optimized the upper arm
of manipulator based on SIMP approach considering dynamic forces at worst position or maximum torque required position [26]. Multi-objective topology was used to optimize serial robot considering dynamic loading conditions using HyperWorks commercial software [27, 28]. Yao et al. optimized upper arm of the RB20 industrial robot experimentally using ABAQUS software at most unfavourable condition [29]. Recently, Srinivas et al. considered 1-DOF manipulator-link, optimized topologically at all angular positions considering dynamic loadings and synthesized a single topology using a weighted density method [30]. The Robotic arm was optimized at volume fraction 0.5 considering dynamic forces; however, the position of the manipulator link was fixed at a horizontal position [32]. Table 2 shows the dynamic analysis of topology optimization.

| Author             | Year | Document type | DOF | Robot Type   | Reduction | Application  |
|--------------------|------|---------------|-----|--------------|-----------|--------------|
| Albers et al. [22] | 2007 | Conference    | 21  | Humanoid     | Mass: 30% | Dishwasher   |
| Albers et al. [23] | 2007 | Journal       | 21  | Humanoid     | Mass: 15% | Kitchen      |
| Albers et al. [24] | 2008 | Conference    | 21  | Humanoid     | Mass: 15% | Industrial   |
| Huang et al. [25]  | 2012 | Journal       | 5   | Manipulator  | Mass: 13.9% | Industrial   |
| Yunfei et al. [26] | 2016 | Journal       | 5   | Manipulator  | Mass: 44.4% | Industrial   |
| Chu et al. [27]    | 2016 | Conference    | 6   | Serial Robot | Weight: 7.1% | Assembly Line |
| Liang et al. [28]  | 2017 | Journal       | 6   | Manipulator  | Mass: 5% | Industrial   |
| Yao et al. [29]    | 2019 | Journal       | 6   | RB20 Robot   | Mass: 17.9% | Pick and Place |
| Srinivas et al. [30]| 2019 | Conference    | 1   | Manipulator  | Volume: 50% | Industrial   |
| Luo et al. [31]    | 2019 | Journal       | 6   | Manipulator  | Mass: 62.6% | Welding      |
| Srinivas et al. [32]| 2020 | Conference    | 1   | Robotic Arm  | Weight: 50% | Industrial   |

3. Trajectory optimization

Trajectory optimization is the development of an optimal path or trajectory that improves energy efficiency or minimizes the processing time. The objective function of the trajectory optimization can be vibration levels, work cycle time, and torque/force requirement. Such trajectory optimization problems can be classified in the area of point to point (PTP) trajectory or continuous path (CP) trajectory problem.

3.1. Point to point trajectory optimization

In a robot work-volume, end-effector changes from an initial point to the endpoint in PTP trajectory. In this process, the master controller interpolates path of end-effector. These types of robots are used for resistance welding, palletization, and pick and place operation, etc. [33]. The PTP trajectory optimization is performed using approaches such as direct approach and indirect approach. In the direct approach, the trajectory control problem is solved using a non-linear programming method. Hargraves and Paris initiated the use of a direct approach to solve a constrained parameter problem for trajectory optimization [34]. However, the obtained accuracy level was lower and the solution was suppressed by local minima pre-set in the solution domain. Recently, the direct approach is used by considering motor and auxiliary losses as the objective function [35-37]. The inverse/indirect approach of trajectory optimization problem is solved in three stages. In first stage both sufficient and necessary constraints are constructed systematically for optimality. In second stage, these conditions are discretized to build a constrained parameter based trajectory optimization problem. In third stage, using calculus of variations/maximum principle methods, the trajectory optimization problem is solved. For robotics system indirect approach is efficient compared to the direct approach [38-42]. The trajectory optimizations for such a process are performed considering the optimum trajectory and cycle time [43, 44].
3.2. Multi-point trajectory optimization
In multi-point or continuous path trajectory optimization represents the movement of end effector through intermediate points from starting to end. Welding, camera movement in quality inspection, painting, etc. are the examples for multi-point trajectory optimization. The minimization of energy consumption in this aspect is achieved using optimization of path, timing or both [45-49]. In a few cases, trajectory optimization is achieved considering a multi-objective function in B-splines [50, 51]. In these type of methods objective function can be selected as shortest time, minimum energy consumption, and maximum energy efficiency. To solve the objective function multiple constants can be selected such as; angle, velocity, acceleration, and torque etc. Few attempts are made in the field of commercial integrated robots to compare the results of their optimization algorithm [52, 53].

4. Light-weight robotic components
The weight of the robotic structural components plays an essential role in the dynamic performance of the industrial manipulator. However, a significant change in robotic arm weight causes balancing and accuracy problems. Initial attempts are made to overcome the stated issues by analysing 2-3 DOF robotic arms using counterbalancing and simulation of the accuracy [54, 55]. Chalhoub et al. investigated the inherent difficulty of the robotics arms that is vibrations and control [56]. Recently, the light-weight components of the robotic arms are optimized and analysed [57-60]. Kolyubin et al. analysed consistent of kinematic and dynamic calibration for the redundant lightweight industrial manipulator [61]. Mina et al. placed all motors at the base to avoid the additional mass on the manipulator-links. Hence, the arms become lighter and maximum torque of each joints has been minimized [62]. However, most of these methods convert rigid members into the flexible members and shifted the robotic arms into the domain of flexible manipulators.

5. Conclusion
The demand for electrical energy was significantly increased in the sector of industrial robots due to its usage. Various approaches were proposed to overcome the stated problem, such as; minimization of material using topology optimization, selection of optimal path using trajectory optimization, and usage of light-weight robotic components, etc. Different methods and techniques have been revised as well as primary outcomes are highlighted in the proposed approaches. On one hand, the topology optimization found in literature organized into two groups based on loading conditions, namely static analysis, and dynamic analysis. On the other hand, trajectory optimization mainly focused on the optimization of path, which is categorized into point-to-point optimization and multi-point/ continuous path optimization. Finally, the usage of light-weight structural components has been presented in the field of industrial manipulators. The topology optimization method currently seeing a growth of significant and novel solutions to improve energy efficiency in the field of industrial manipulators. From existing literature, the topology optimization method helps to minimize energy consumption substantially compared to the other two techniques. This review paper was helpful in selecting and understand the different approaches used to improve the energy efficiency of industrial robots.

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