

## GA-Driven Structural Optimization of Lightweight Mechanical Linkages

Dr. Rajesh Kumar P<sup>1\*</sup>, Dr.SP.Arunkumar<sup>2</sup>, A.C. Ramkumar<sup>3</sup>, A.Rufina<sup>4</sup>, Allocious Britto Rajkumar R<sup>5</sup>, V.Rajasubramanian<sup>6</sup>,

<sup>1\*</sup>Assistant Professor, Department of Mechanical Engineering, MVJ College of Engineering, Bangalore.

[prajeshkumarmvjee@gmail.com](mailto:prajeshkumarmvjee@gmail.com)

<sup>2</sup>Professor, Department of Mechatronics Engineering, Nehru Institute of Engineering and Technology, Coimbatore.

[arungreesma@gmail.com](mailto:arungreesma@gmail.com)

<sup>3</sup>Assistant Professor, Department of Mechanical Engineering, Nehru Institute of Engineering and Technology, Coimbatore.

[profram.ac@gmail.com](mailto:profram.ac@gmail.com)

<sup>4</sup>Assistant Professor, Department of Artificial Intelligence and Data Science, Dhanalakshmi Srinivasan College of Engineering,

Coimbatore. [rufijohny28@gmail.com](mailto:rufijohny28@gmail.com)

<sup>5</sup>Assistant Professor, Department of Aeronautical Engineering, Nehru Institute of Technology, Coimbatore. [britto.aero@gmail.com](mailto:britto.aero@gmail.com)

<sup>6</sup>Assistant Professor (SG), Department of Aeronautical Engineering, Nehru Institute of Technology,

Coimbatore. [rishirajaraja@gmail.com](mailto:rishirajaraja@gmail.com)

**Corresponding Author:** [prajeshkumarmvjee@gmail.com](mailto:prajeshkumarmvjee@gmail.com)

### Abstract

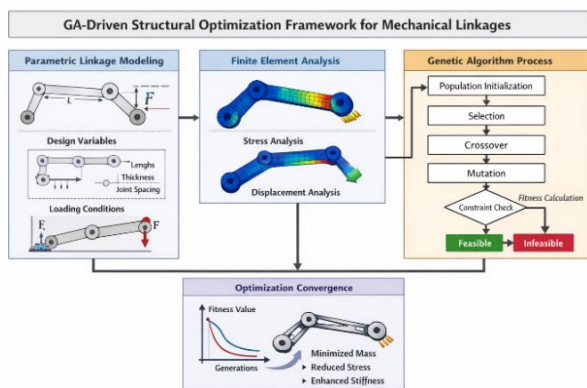
Lightweight mechanical linkages are one of the most vital elements of the modern engineering system since mass reduction is closely related to the energy efficiency, dynamic characteristics, and structural life. The traditional methods of designing linkages would normally use the conservative safety factors and tuning of the parameters manually and, as a result, the extent to which a weight reduction could be achieved without reducing the stiffness and strength is restricted. The proposed paper provides the systematic weight minimization of a planar mechanical linkage in Genetic Algorithms (GA) model of structural optimization under realistic mechanical constraints applied. The suggested methodology combines parametric geometric modeling with structural assessment by means of finite element analysis, therefore, allowing the optimization of the dimensions of the links simultaneously, in accordance with stress, displacement and buckling requirements. The GA formulation uses a multi-objective optimization criterion which is a compromise between mass reduction and structural integrity and kinematic performance. Variables of design include the parameters of link cross sections, material distribution, joint spacing with the allowable stresses and functional motion conditions to be enforced. The optimization process provides light but mechanically robust solutions when they are obtained with the help of mutation, crossover, and selection of candidate solutions. Findings indicate the degree of mass reduction compared to baseline designs with optimized linkages with better ratios of stiffness to weight and lesser concentrations of stress dispersed at peaks. The GA based system provides a scalable and automatable design tool to robots, deployable mechanisms, and high speed mechanical fabrication. This paper has laid a plausible foundation of streamlining the next-generation weight-cutting linkage systems, which incorporate the performance, durability, and material effectiveness in one system.

**Keywords - Genetic Algorithm; Structural optimization; lightweight design; mechanical linkages; multi-objective optimization; finite element analysis; stress-constrained design.**

### I. INTRODUCTION

Leverage-type Lightweight mechanical This type of linkage is used to assemble many engineering systems, such as robotic manipulators, deployable mechanisms, automotive subsystems, aerospace actuation units, and precision manufacturing equipment. In these applications, the decrease in structural mass directly increases dynamic performance, energy efficiency and controllability at the same time decreases material consumption and costs of operation[1]. Nevertheless, violent weight loss tends to produce a rise in the stress concentration, over-deflection, decreased fatigue life and dirty reliability unless performed in an exact design structure[2]. Therefore, the establishment of the optimal balance between the lightweight design and structural integrity has become a key concern of the development of the modern mechanical systems[3]. The conventional linkage design techniques normally depend on analytical rules of sizing, rules of thumb safety factors, or trial-and-error methods with finite element analysis. Although these are successful in the case of conservative designs, they are unable to search large design spaces with multiple geometric variables, nonlinear constraints, and conflicting objectives[4]. With the development of mechanical linkages with faster speeds, decreased inertia and reduced volume, these traditional methods prove to be more inefficient and susceptible to less efficient solutions. Also, manual optimization is quite designer-influenced and is not scalable to more complicated multi-link mechanisms with strict performance requirements[5]. Recent developments in computers intelligence have made the use of metaheuristic optimization methods in complex engineering design problems possible. Genetic Algorithms (GAs) are especially appealing among these methods, as they are capable of a population-based search, will not be sensitive to local optima and can be applied in nonlinear, multi-modal optimization landscapes[6]. GAs are able to successfully exploit large parametric spaces and find high-quality solutions, which would be hard to reach using gradient-

based or deterministic optimization, by simulating the process of evolution as indicated by selection, crossover, and mutation. GAs can provide an excellent design optimization platform with constraints and are automated when used together with structural analysis tools. Regardless of these benefits, GA-based optimization of mechanical linkages is frequently constrained to a form of kinematic optimization or one-objective optimization, and the structural performance indicators of stress distribution, stiffness, and displacement limits are not appropriately considered[7]. In most of the designs that are reported, mass is reduced without a thorough evaluation of load bearing capacity in the real operating conditions. This poses a high-priority disjunction between theoretical optimization results and real-world and deployable designs of linkage applicable to real-world mechanical systems[8]. The general GA-based structural optimization model that is used in the study is depicted in Figure 1.



**Figure 1 GA-Driven Structural Optimization Framework**

In order to fill this gap, this paper offers a framework of structural optimization by the use of GA on lightweight mechanical linkages where structural constraints are explicitly considered in the evolutionary optimization process. The methodology combines parametric geometric

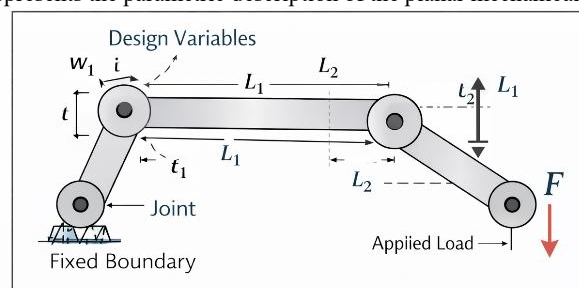
modeling, structural assessment using finite elements and multi-objective GA optimization to ensure that the mass is minimized with reasonable stress level and deformation properties[9]. The main contributions of the work include three points: (i) development of a powerful GA-based optimization strategy that is specialized on structural linkage design, (ii) the systematic incorporation of stress and displacement constraints that promote mechanical reliability, and (iii) the evidence of the better stiffness-to-weight performance of the linkage configurations than the baseline ones. It is a next-generation lightweight mechanical linkage design architecture that is built upon a scalable and automation able solution.

## II. LITERATURE SURVEY

The concept of lightweight structural design has become a leading research concern in the modern mechanical engineering field due to the growing need to achieve high-speed performance, low-energy use, and increase the efficiency of the system in the robotic, automotive, and aerospace industries and fields. Mechanical linkages as elementary elements of motion transfer are highly sensitive to the change of the mass and stiffness; the extra mass directly leads to the deterioration of dynamic response, higher power consumption by actuators, and faster wear of joints. As a result, there have been intensive studies on creating systematic optimization strategies to reduce the mass of structures by not compromising the mechanical integrity[10]. The initial studies of linkage optimization were largely based on the analytical equations and deterministic sizing processes, where the dimensions of links were varied as per the simplified stress and deflection equations. Although these methods provided practical design rules, they were limited in dealing with a complicated geometry, nonlinear constraints and multiple conflicting goals. As its wider availability became possible, the widespread availability of finite element analysis (FEA) researchers started to use numerical simulation in the design process to better understand how stress is distributed and how a material will deform[11]. However, the process of simulating them commonly relied on trial and error methods, which made the simulation methods computationally expensive and extremely challenging to the design expertise. In order to overcome these constraints, design methods based on optimization have been suggested, in particular gradient-based and mathematical programming. Gradient-based techniques are also very sensitive to starting conditions as well as more likely to get stuck on local optima, particularly in very nonlinear problems like mechanical linkages although they work effectively in convex, well-posed problems[12]. Also, discrete elements of the design, manufacturing, and nonlinear stress constraints further limit their practical use. Over the past few years, metaheuristic optimization algorithms have gained significant attention as a potent means of optimization of structural and mechanical systems. In particular, genetic algorithms (GAs) have been very useful since they have ability to conduct a population-based search and apply to nonlinear, non-convex, and multi-objective problems that do not need gradient information[13]. GA methods have worked well on structures in truss form, frames, compliant mechanisms, and optimization of topology, with large weight savings and structural efficiency of the structure. Their evolutionary character allows them to exhaustively search design space and find out non-standard solutions that can hardly be found with the use of traditional methods[14]. A number of researchers have used GA in mechanical linkage systems with the main aim of kinematic synthesis, precision of motion and optimization of trajectory. These research works optimized the connections between points and locations of joints to meet the prescribed motion paths or transmission properties. But structural factors in terms of stress concentration, loss of stiffness and constraint of displacement were rather secondary or ignored[15]. This caused numerous optimized kinematic designs to be too weak to be used in practice. Still more recent studies have tried to combine GA optimization with structural assessment using finite elements in order to fill this gap. These hybrid constructions exhibited better stress management and better stiffness-weight ratios. However, the current research tended to be single-purpose formulations or simplified treatments of constraints and, therefore, were not scalable and real-world applicable. Moreover, comparative evaluations of baseline and optimized designs were often inadequate and it was hard to measure the real benefits of GA-based structural optimization. Based on the read literature, it is clear that there is an existing research gap in formulating a detailed GA-based structural optimization model of mechanical linkages that at the same time, deals with mass minimization, stress restrictions and displacement regulation. The current work is placed to fill this gap, that is, it combines parametric linkage modeling with finite element, and multi-objective GA optimization in a single and automation-ready framework contributing to dependable and lightweight mechanical linkage design in the sophisticated engineering regime.

## III MECHANICAL LINKAGE MODELING AND DESIGN VARIABLES

The mechanical linkages that are used in this study are the modeled planar articulated systems made of rigid links that are connected by the ideal revolute joints. These types of configurations are commonly used in motion transmission, force amplification and constrained trajectory generation in robotic systems, automated mechanism and lightweight actuation systems. The linkage is modeled to be acting with quasi-static loading conditions of the worst combination of external forces and inertia effects that the linkage is subjected to in service in order to optimize the structure. This assumption is necessary so that the design which will be optimized will be structurally safe at peak operational demands. The parametric modeling method defines the baseline linkage geometry, which allows systematically varying design parameters in the process of optimization. A centerline geometry is used to represent each link to give a cross-sectional profile, thus length, thickness, and material distribution can all be independently controlled. Joints are represented as pin connections with negligible friction and the grounded link has been put under boundary conditions to emulate realistic support constraints. Output link external loads are imposed to model task-dependent force transmission needs (e.g. payload handling or resistive loads of mechanisms coupled to it). Figure. 2 represents the parametric description of the planar mechanical linkage and the planar design variables.



**Figure 2 — Parametric Mechanical Linkage Model & Design Variables**

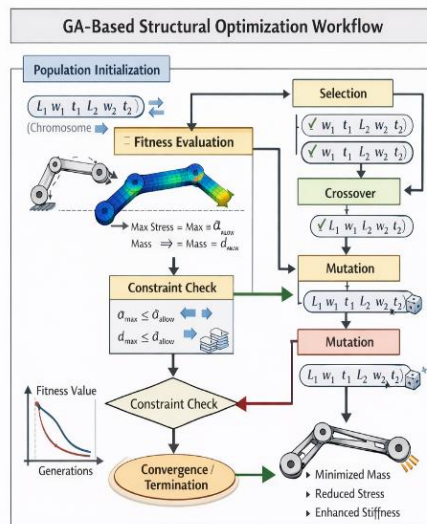
Design variables to be optimized The design variables chosen are important in effective reduction of mass with minimal impact of structural integrity. The main design variables that can be distinguished within the current framework are: (i) link length, that has an effect on the kinematic reach and load paths; (ii) the cross-sectional dimensions of the individual links that determine the bending stiffness and the level of stress; (iii) the distribution of the joint spacing dimensions that affect the force transmission angles and the magnitude of internal loads; and (iv) the spacing parameter of the joints that determine both the kinematic reach and the load paths. All the design variables are constrained to realistic manufacturing ranges and conditions to make them feasible and easy to make.

The material properties are considered as fixed inputs in the analysis to separate the influence of the geometric optimization on the structural performance. The connection is supposed to be made of a light structural alloy, which has known modulus of elasticity, the Poisson ratio, the density and the yield stress. These properties are introduced in a structural analysis step to test the response of stress and deformation of the structure subjected to loading conditions. The optimization process is limited to geometric efficiency and redistribution of loads by maintaining the material constant. Finite element-based analysis is conducted to conduct structural performance assessment of each candidate design

produced by the Genetic Algorithms. The main response parameters that were obtained through the analysis are maximum von Mises stress, nodal displacement peak, and the general mass of the structure. These measurements are later applied to measure the constraint satisfaction and fitness calculation in the optimization process. Stress constraints keep each design within reasonable limits with a reasonable margin of safety, and displacement constraints maintain the accuracy of functionality as well as the precision of motion of the linkage. Such a parametric modeling and variable definition approach makes it easy to have a seamless relationship between geometric design, structural analysis and evolutionary optimization. With the flexibility of design hard-wired into the linkage model, the proposed structure allows exploring the design space efficiently and converging to lightweight, structurally robust linkage designs.

#### IV GA-BASED STRUCTURAL OPTIMIZATION METHODOLOGY

In this paper, structural optimization of lightweight mechanical linkages is conducted by a Genetic Algorithm (GA) because it is well known to solve nonlinear, multi-variable, and constraint dominated problems in the engineering design. GA, unlike gradient-based approaches, does not need the derivative information and can be used to search complex design space with multiple local optima, a feature that is extremely useful in linkage systems with a geometric and structural interaction. The chromosome encoding process of the design variables outlined in Section II is the starting point of the optimization process. Individual solutions, each of which is called an individual, are full linkage configurations that are represented as real valued vectors of link lengths, cross sectional dimensions, thickness distribution parameters and joint spacing variables. Real coded GA is used to prevent the discretization error and improve the accuracy of convergence when very specific geometric parameters are involved. The first population is randomly created within some predetermined limits to provide enough diversity and extensive search of the design space. The formulation of a multi-objective fitness function is based on the need to reduce the structural mass and at the same time meet the requirements of mechanical performance. The main goal is weight reduction, and it is a functional of the link geometry and density of the material. The structural constraints are integrated in the form of penalty-based formulations taking into consideration the maximum von Mises stress and peak displacement of the finite element analysis. The designs that exceed the permissible stress or displacement levels are penalized by fitness values, thus driving the evolutionary process to structural viable designs. This handling constraint strategy guarantees that optimized design is not only mechanically sound when loaded with the prescribed loads. Figure. 3 outlines the specific workflow of the structural optimization performed by GA.



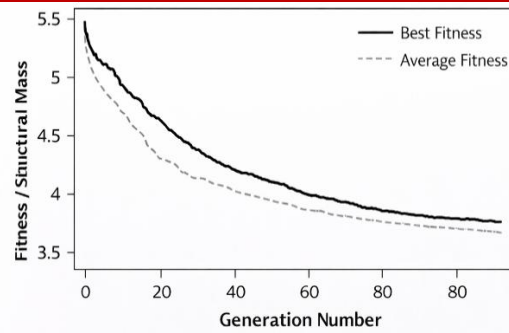
**Figure 3 GA-Based Structural Optimization Workflow**

The genetic algorithm operators that are traditional determine the evolutionary process. Selection is done through a tournament system where only the fittest individuals are selected in the process and population diversity is maintained. In crossover operations, parent chromosomes are recombined to produce offspring with desired traits of several high-performing designs. A dynamic crossover probability is used when the generations begin to start and boost the overall search effectiveness, and later local refinement. The probability of mutation is low, which is used to add controlled stochastic variation to prevent premature convergence and allow exploration of the unexplored areas in the design space. Finite element structural assessment is applied to each new generation of individuals. Linkage geometry is automatically updated depending on decoded design variables, and mesh generation, boundary condition assignment is performed followed by load application. The parameters of structural response, i.e., mass, stress distribution and displacement, are calculated and fed back to the GA engine to evaluate fitness. This is a closed-loop interaction between the structural analysis and the GA which guarantees constant goal-driven optimization. The algorithm is continued until some predefined termination criterion is met, like the achievement of some specific number of generations, or the fitness increase between consecutive executions becomes negligible. The resultant product is a fine-tuned linkage design that illustrates a significant decrease in mass but still has reasonable stress and stiffness properties. This GA-based methodology offers a model of systematic, automated, and scalable optimization of lightweight mechanical linkages and can be easily generalized to more complicated multi-link systems or to other performance targets.

#### V. RESULTS AND DISCUSSION

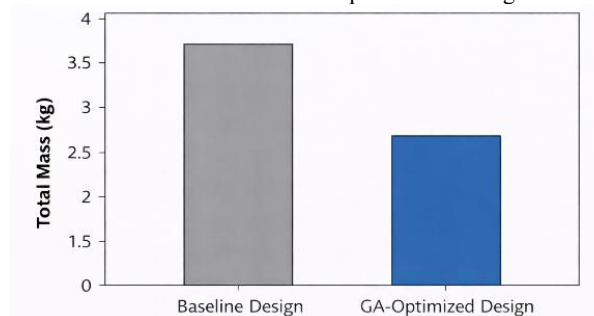
The effectiveness of the proposed framework of structural optimization using GA is assessed by comparing the optimized mechanical linkage arrangement with the one that was not optimized (baseline) with the same loading and boundary conditions. It discusses the mass reduction, stress redistribution, displacement behavior and convergence properties on the optimization process with emphasis on the structural benefits of the evolutionary optimization process.

**5.1 Genetic Algorithm Convergence Behavior:** The Genetic Algorithm has stable and consistent convergence between generations. In the first generations, the objective function decreases quickly because of exploration of the design space globally. The stage is characterized by immense changes in the geometric parameters where the mass is reduced substantially without imposing penalty to the constraints. The change of the rate of improvement in the fitness curve as the algorithm goes on, shows that exploration is being replaced by exploitation. Fine-tuning of the thickness of the links and the cross-sectional dimensions becomes prevalent in subsequent generations and leads to small but significant gains in the stiffness to weight ratio. The convergence trend is smooth indicating that the formulation of the GA is robust and that real-coded chromosomes are applicable to continuous structural variables. Figure 4 depicts the convergence behavior of the GA as the optimization process happens.



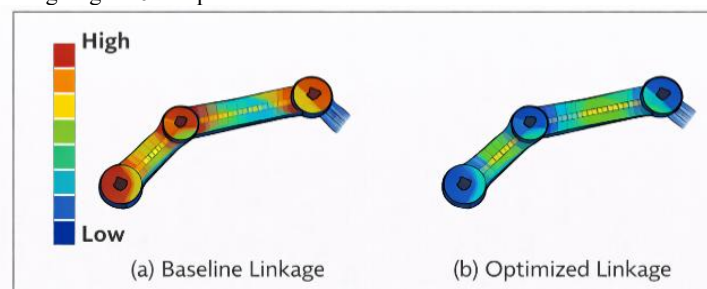
**Figure 4 — GA Convergence Characteristics**

**5.2 Mass Reduction and Structural Efficiency:** The main goals of the optimization were the mass reduction in general of the mechanical linkage. The optimized structure realizes significant decrease in total mass relative to the base configuration mainly in a form of strategic decrease of material in areas of low stress and redistribution to areas of high load. In contrast to uniform scaling methods, the GA can be used to find non-intuitive geometric blends which can be rigid but with zero extra material. This also leads to a much higher stiffness-to-weight ratio being of high importance in high-speed and dynamically actuated mechanisms. The obtained results clearly show that the mass reduction can be conducted without breaking stress or displacement constraints, which proves the successfulness of the constraint-handling strategy. As Figure 5 illustrates, a comparison of the overall structural mass between an optimization design and a baseline design is presented.



**Figure 5 Baseline vs Optimized Mass Comparison**

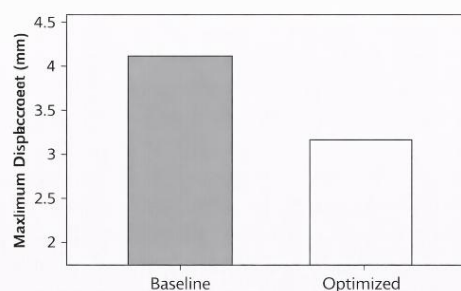
**5.3 Stress Distribution and Load Transfer Characteristics:** The results of the Finite element stress analysis indicate that there is a significant change in the distribution of stress on the optimized linkage. The uniform cross-sectional assumptions between uniform stresses at joint interfaces and mid-span points in the baseline design make the design to experience localized peak stresses. Conversely, the optimized design has a better uniformity of the stress distribution, where the highest von Mises stress values are drastically lowered and redistributed across the length of the link. This is explained by variation of GA-based thickness and optimized joint distance, which is highly efficient in matching the load tracks to structural rigidity. Notably, the value of all the stresses is lower than the allowable material limit, which proves the mechanical safety in worst-case loading. Figure 6 compares the von Mises stress distribution of both baseline and optimized linkages.



**Figure 6 Stress Distribution Comparison**

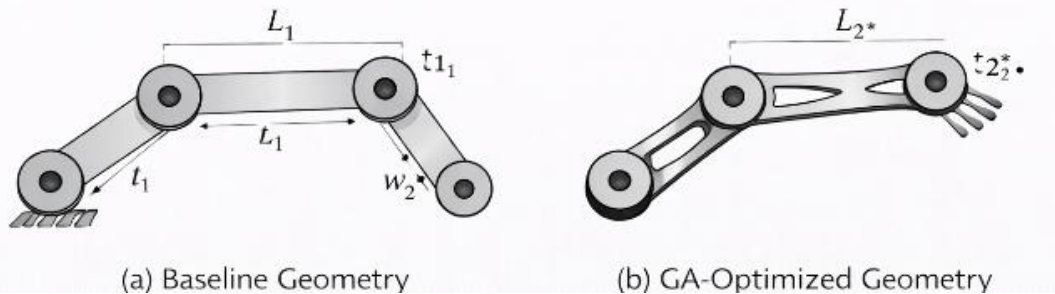
#### 5.4 Displacement and Stiffness Performance

The displacement analysis shows that the optimized linkage has similar, and in certain areas better than base design, stiffness. The peak nodal displacement at the output link is within the set functional tolerance in spite of the considerable reduction of the mass. It shows that the positional accuracy and the kinematic reliability are not compromised by the optimization process. The higher stiffness to mass ratio is especially beneficial in precision applications, which is subject to inaccuracy in movement and control in case of uncontrolled deflection. The findings affirm the effectiveness of the weight reduction with mechanical rigidity competing goals optimized using GA. Figure 7 gives the maximum nodal displacement comparison of the same loading conditions.



**Figure 7 Maximum Displacement Comparison**

**5.5 Discussion on Design Implications:** The results obtained show that structural optimization with the help of GA should allow redistribution of materials that are not even across all aspects but based on the specifics to perform a lightweight design, which in turn is one of the main limitations of standard lightweight design strategies. Optimized linkage has a lower mass, better stress distribution and displacement behavior has control, which means it is highly desirable when great dynamic performance and long life is needed. The evolutionary model also offers the flexibility to add more goals, including fatigue life or manufacturability limit without a change in the fundamental methodology. All in all, the findings indicate that the proposed solution is a viable and scalable and automation-friendly solution to the design of advanced mechanical linkage. Figure 8 displays a visual comparison of linkage geometries baselines and GA-optimized ones.



**Figure 8 Baseline vs GA-Optimized Geometry**

## VI. CONCLUSION

This paper introduced a structural optimization framework of lightweight design of mechanical linkages based on GA, and tackled the trade-off of paramount importance in mechanical linkage design, that of reducing mass and maintaining structural integrity. The proposed methodology can facilitate the systematic exploration of complex design spaces that are not easily examined with conventional deterministic methods through the combination of parametric geometric modeling, finite element-based structural analysis, and a real-coded Genetic Algorithm. The results of the optimization prove that the large percentage of mass can be saved by means of intelligent redistribution of materials instead of the standard dimensional scaling. When compared to the baseline design the GA-optimized linkage had a significantly better stiffness to weight ratio, lower peak stress concentrations and was able to control the displacement behavior with the same loading conditions. The convergence property ensured the soundness and consistency of the GA formulation as there was steady increase in fitness values over generation and no premature convergence was observed. The explicit stress and displacement constraints were included to make sure that any design of the optimisation is mechanically feasible and applicable in practice. Compared to the conventional methods of lightweight design that tend to compromise reliability, the given framework maintains the functional accuracy and structural safety and results in significant weight-saving. These findings emphasize the capability of evolutionary optimization to find non-intuitive geometric designs that can be used to maximize the efficiency of load transfer and structural performance. In general, the developed GA-based optimization model provides a scalable, automation-compatible design system of next-generation mechanical linkages in robotics, precision machine, high-speed mechanical assemblies. Further developments of this study can be fatigue-life aspects, dynamic loading environments, and multi-material optimization to expand the relevance of the framework to the real-world engineering systems.

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