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STRUCTURAL INVESTIGATION OF PNEUMATIC GRIPPERS FOR HANDLING AUTOMOTIVE PARTS USING FINITE ELEMENT ANALYSIS AND TOPOLOGY OPTIMIZATION

OTOMOTİV PARÇALARININ TAŞINMASINDA PNÖMATİK TUTUCULAR: YAPISAL İNCELEME, SONLU ELEMANLAR ANALİZİ VE TOPOLOJİ OPTİMİZASYON

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ABSTRACT

Robotic grippers are widely used in the automotive industry for material handling processes. The lightweight, durable, and efficient design of these grippers is a critical factor for optimizing production operations. This study investigates the structural performance of a pneumatic gripper mechanism designed for a 500 kg material handling system, specifically for handling automotive parts. Finite element analysis (FEA) was used to evaluate the gripper's ability to withstand applied loads without compromising its structural integrity. The initial analysis revealed a safety factor of 5.16, confirming the design's safety under an applied pressure of 5 bar. Following topology optimization, the gripper's mass was reduced by 35%, resulting in a slight increase in the stress concentration and a decrease in the safety factor to 4.72. To better understand the benefits of topology optimization, a dimensionless SF/M ratio was introduced, which compares the relative safety factor per unit mass for both designs. The initial design served as the baseline with an SF/M ratio of 1.0, while the optimized design achieved a ratio of 1.42, indicating a 42% improvement in structural efficiency. This research demonstrated the effectiveness of FEA and topology optimization in optimizing gripper designs for material handling applications, emphasizing the importance of maintaining a sufficient safety factor. While the optimized design results in higher stress, it maintains structural integrity and reduces the mass, ensuring that the gripper can securely handle loads. These improvements ultimately enhance the functionality and efficiency of robotic grippers in industrial environments.

Keywords: Gripper, finite element analysis, topology optimization

ÖZET

Robotik kavrayıcılar, otomotiv sektöründe malzeme taşıma işlemlerinde yaygın olarak kullanılmaktadır. Bu kavrayıcıların hafif, dayanıklı ve verimli tasarımı, üretim süreçlerinin optimize edilmesi açısından büyük öneme sahiptir. Bu çalışma, otomotiv parçalarının taşınması için tasarlanmış 500 kg kapasiteli bir malzeme taşıma sistemi için pnömatik kavrayıcı mekanizmasının yapısal performansını araştırmaktadır. Sonlu elemanlar analizi (SEA), kavrayıcının dayanım şartlarını karşılayarak uygulanan yükleri güvenle taşıyabilme yeteneğini değerlendirmek amacıyla kullanılmıştır. İlk analizde, 5 bar basınç altında sistemin güvenli olduğunu gösteren 5,16 güvenlik faktörü hesaplanmıştır. Daha sonra yapılan topoloji optimizasyonu ile sistemin kütlesi %35 oranında azaltılmış, bu süreçte güvenlik faktörü çok az bir düşüşle 4,72 olmuştur. Topoloji optimizasyonunun faydalarını daha iyi anlayabilmek için, her iki tasarım için güvenlik faktörünün birim kütle başına göre karşılaştırılmasını sağlayan boyutsuz bir SF/M

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oranı tanıtılmıştır. İlk tasarım, 1.0 SF/M oranı ile referans alınırken, optimize edilmiş tasarım 1.42 oranına ulaşmış ve bu, yapısal verimlilikte %42'lük bir iyileşmeyi göstermektedir. Bu çalışma, SEA ve topoloji optimizasyonunun malzeme taşıma uygulamaları için kavrayıcı tasarımlarını optimize etmedeki etkinliğini göstermekte olup, güvenlik faktörünün yeterli seviyede tutulmasının önemini vurgulamaktadır. Optimize edilmiş tasarım, kütleyi azaltırken gerilme seviyesinde bir artışla birlikte yapısal dayanımı korumuş ve kavrayıcının yükleri güvenli bir şekilde taşımasını sağlamıştır. Böylece, endüstriyel ortamlarda robotik kavrayıcıların işlevselliği ve verimliliği artırılmıştır.

Anahtar Kelimeler: Kavrayıcı, sonlu elemanlar analizi, topoloji optimizasyonu

INTRODUCTION

Automation systems are commonly used in contemporary industrial applications, especially in the automotive sector, to handle and assemble parts. These systems efficiently grasp and manipulate parts with the help of grippers. The grippers are driven by hydraulic or pneumatic actuators. They can be designed in a variety of ways to serve different parts of the body. Productivity and operational reliability depend on the efficiency and accuracy of material handling systems.

Grippers are essential parts of robotic and automated systems. They provide the interface between the machine and the target material. These devices must be sufficiently precise and powerful to handle all kinds of materials, from fragile electronic parts to heavy industrial parts with different geometries. As the primary functional component at the end of most robots, grippers play a crucial role in system performance. Since grippers perform the majority of the actual handling, system performance is affected by both design and functionality, which can affect speed, accuracy, and quality.

Grippers must withstand a variety of operational environments and interface with many types of materials and products. Having a secure hold over material that does not harm it is important, particularly within sectors that value accuracy, including electronics, pharmaceuticals, and automobile manufacturing. Using grippers with high-end control systems allows for precise manipulation and placement of materials on the assembly line, thereby improving the process efficiency and reducing downtime. There are different grippers for capturing various types of workpieces, thus making production lines more flexible. Finger grippers are the most popular, followed by vacuum and magnetic grippers. Each type has advantages and disadvantages, depending on the particular case. The grippers must meet the strength requirements of the static, dynamic load, and fatigue load. Grippers are required to withstand static loads, which include the weight of the parts and the forces applied by pneumatic or hydraulic actuators. The stress and strain limits must also be checked. The gripper components have to be designed with consideration of stresses and deformations.

Grippers also need to withstand dynamic forces such as vibrations and impacts. Their strength is assessed by considering the fatigue and fracture limits. Fatigue occurs when a material weakens over time due to repeated stresses, whereas fracture refers to the breaking of the material. The grippers must stay within these limits. Grippers should be able to endure long-term use. This durability is checked against fatigue and wear boundaries; therefore, it is crucial for the design of gripper components to meet these requirements. An analysis of grippers' strengths is necessary to ensure that they adhere to these standards. This can be achieved using various techniques, such as Finite Element Analysis (FEA). FEA helps determine the stress and deformation patterns by considering the geometry and material properties of the gripper.

Topology optimization is now used to improve gripper functionality and performance. Optimized grippers are useful for grasping and repositioning objects of various weights, sizes, and shapes. Applying topology optimization to gripper design involves outlining the requirements and limitations of the gripper system, including its ability to withstand loads and maintain stability during operation. To optimize the stiffness and strength while reducing the stress concentration, the material distribution within the gripper’s design space must be adjusted. This approach not only enhances the gripper's capability to handle diverse objects but also reduces energy consumption, and improves the overall efficiency of robotic applications. Topology optimization design is a valuable tool for developing high-performance grippers. By optimizing the material distribution, it is possible to methodically design grippers. This method can generate innovative holder designs with high performance and lighter mass. Thus, gripper design can provide more effective gripper systems for robots and machines.

The design and optimization of robotic grippers have seen substantial advancements in recent years, with various approaches addressing the limitations of structural strength, adaptability, and efficiency. Bhatt and Chauhan, (2016) introduced a two-finger friction gripper for a wheel mobile robot, focusing on pick-and-place tasks and exploring mechanical design parameters like von Mises stress, deformation, and torque. This foundational study demonstrated the significance of gripper design for industrial applications requiring precise object manipulation. Building on this, Bhagawati et al., (2022) employed finite element analysis (FEA) to enhance the structural understanding of mechanical grippers. The study used SolidWorks and ANSYS to focus on the static structural properties of mating gears, claws, and the overall gripper model, offering a more in-depth exploration of how these components withstand stress during operation.

Gürkal et al., (2021) then expanded the discussion by analysing autonomous mobile robot chassis designs, emphasizing the importance of ensuring load capacity independence. This work underscores the broader need for durability and robustness in robotic systems, laying the groundwork for further optimization efforts. More recent studies have introduced innovative approaches. Wang et al., (2024) proposed a reconfigurable gripper with rigid-flexible states, thus addressing the limitations of existing rigid and flexible grippers. The proposed design demonstrated the versatility of switching between states, which improves task adaptability. Similarly, Trinh et al., (2024) developed a gripper that combines rigid and soft components, enabling the safe handling of diverse objects under harsh vibration conditions. The combination of structural stiffness and flexibility in these grippers represents a novel frontier in robotic manipulation technology.

Soft robotics was further advanced using R. Wang et al., (2020) utilized topology optimization and FEA to design a cable-driven soft robotic gripper. This study addressed complex contact nonlinearities, enabling finer manipulations and adaptive grasping. The use of novel boundary conditions and hyperelasticity techniques improved the gripper's ability to handle various tasks. Dörterler et al., (2021) optimized robot gripper designs using multi-objective metaheuristic algorithms to improve the force transmission and minimize the force differences at the gripper ends. The performance of these algorithms demonstrates the value of computational optimization in enhancing gripper efficiency. Yıldırım and Akay, (2024) proposed a Multi-Strategy Arithmetic Optimization Algorithm (MSAOA), which enhances the AOA by introducing a modified update mechanism and a self-adaptive multi-strategy framework. MSAOA demonstrated superior gripper design optimization, allowing for minimal manipulation and secure object handling without damage. Their algorithm outperformed other contemporary methods, offering a more balanced exploration-exploitation trade-off, which is essential for designing industrial grippers that require precision and care.

The present study focuses on the static strength analysis and topology optimization of a gripper driven by a pneumatic cylinder. This gripper is designed to hold automotive parts at three points under 5 bar pressure. By employing FEA, this study investigates the stress and deformation distributions based on the gripper's geometry and material properties, ensuring that the components stay within safe operational limits.

The key objective of this study is to enhance the gripper's design through topology optimization, aiming at reducing its weight while maintaining its structural integrity. First, a static strength analysis of the initial design is conducted to determine the maximum von Mises stress and safety factor. Then, topology optimization is performed to minimize the weight by redistributing the material in regions of low stress. A comparison between the initial and optimized designs is carried out based on the stress distribution, displacement, and safety factors to evaluate the trade-offs.

Unlike previous research, which has primarily focused on either stress reduction or displacement control, this study addresses the critical trade-off between increased stress and structural displacement in gripper design. By applying topology optimization, this study aims to balance mass reduction with sufficient safety margins, ensuring that grippers can reliably handle automotive parts without compromising performance under operational loads. The novelty of this research lies in the integration of mass reduction strategies with FEA and topology optimization, offering new insights into achieving lightweight and robust gripper designs.

NUMERICAL STUDIES

The structural performance of the pneumatic gripper system was analysed using SolidWorks simulations. The methodology involved creating a detailed 3D model, performing static strength analysis under appropriate boundary conditions and loads, and conducting topology optimization to reduce weight while maintaining structural integrity. Alloy steel, with a yield strength of 620 MPa, was used as the material for the gripper. The analyses compared initial and optimized designs based on stress distribution, displacement, safety factors, and mass reduction.

Topology Optimization Methodology

In this study, the topology optimization of the pneumatic gripper was conducted using a detailed and problem specific approach aimed at improving structural performance while minimizing material usage. The focus of the optimization process was to maximize the gripper's stiffness, minimize its weight, and ensure the structure could safely handle automotive parts under operational loads.

Problem Definition and Design Setup

The design space for the gripper was defined based on the operational requirements of handling automotive parts. The allowable design space was determined by the geometric constraints of the gripper's design, such as the attachment points and the gripper arms' structural limits. The primary goals were set to minimize the gripper's weight while maintaining sufficient structural integrity, as measured by the von Mises stress distribution and the safety factor (Larsson et al., 2022).
The constraints were established to reflect the real-world operating conditions of the gripper, including:

- Maximum allowable stress: The material's yield strength was set as the upper limit for von Mises stress.
- Displacement constraints: The displacement of critical points, particularly at the gripper arms where contact with automotive parts occurs, was constrained to ensure proper handling.
- Manufacturing constraints: Given the application, the final design had to be manufacturable using conventional processes, ensuring that complex geometries did not exceed feasible limits.

Topology Optimization Process

The topology optimization was performed using the Solid Isotropic Material with Penalization (SIMP) method. This method iteratively redistributes material within the design space to maximize stiffness while reducing unnecessary mass. The following steps were followed during the optimization process:

- Initial Material Distribution: The entire design space was filled with material at the beginning of the optimization process.
- Objective Function: The optimization algorithm aimed to minimize the gripper's mass while ensuring that the stiffness and strength were maintained. The objective function was set to maximize stiffness under the applied loads while minimizing the overall material usage.
- Optimization Algorithm: The SIMP method, which penalizes intermediate density values, was used to ensure the design converged towards a structure made of either solid material or voids, thereby avoiding inefficient material distribution.

Constraints and Iterative Refinement

The optimization was subject to constraints that prevented the stress from exceeding the yield strength of the material and kept the displacement within allowable limits. The optimization algorithm iteratively adjusted the material layout, removing material from low stress regions while reinforcing high stress areas. The convergence criteria for the optimization were based on:

- Stability of the objective function: The optimization stopped when the changes in the objective function value (i.e., stiffness and mass) between iterations became negligible.
- Satisfaction of constraints: The process ensured that all stress, displacement, and manufacturability constraints were satisfied before concluding.

In addition to evaluating traditional metrics such as stress, displacement, and Safety Factors (SF), a dimensionless SF/M ratio was introduced to quantify the efficiency improvements achieved through topology optimization. This ratio compares the relative safety factor per unit mass for both the initial and optimized designs, as defined in Equation (1).

$$\boldsymbol{SF/M = \frac{SF_{optimised}/M_{optimised}}{SF_{initial}/M_{initial}}} \tag{1}$$

where SF/M is a dimensionless ratio representing the structural efficiency of the gripper design, defined as the safety factor per unit mass. $M_{\text{optimised}}$ represents the mass of the optimized design, and $\mathrm{M}_{\text{initial}}$ represents the mass of the initial design. This ratio provides a comparative metric to evaluate the trade-offs between safety and weight reduction achieved through topology optimization.

Computational Model and Boundary Conditions

Figure 1a illustrates the gripper mechanism when lifting a material weighing around 500 kg. The grippers hold the material via a pneumatic cylinder, which applies a pressure of 5 bar to ensure a secure grip and prevent rotation around the axis due to the resulting moment. Thus, with the designed mechanism, the material is held in three different zones with rubber, as shown in Figure 1b. For the analysis, a single gripper was simplified by retaining only the parts affected by the load (Figure 1b).

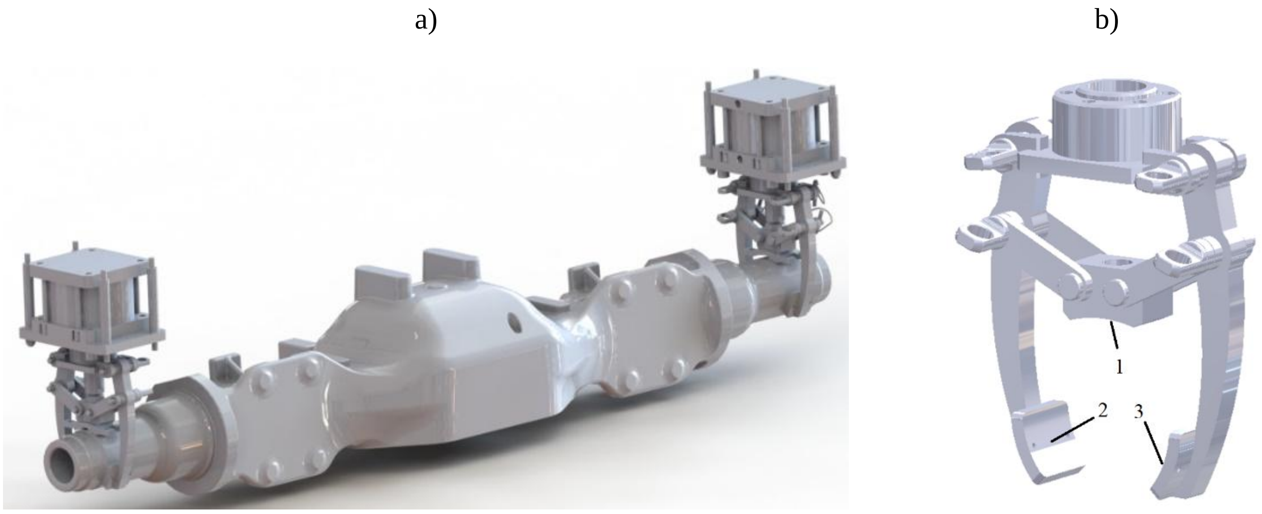

Figure 1. a) Material to be Lifted by a Gripper; b) Single Gripper used for Analysis

Figure 2 shows the motion mechanism of the gripper. When the gripper is fully open, there is a gap of 170.81 mm between the cylinder piston and an aperture of 57.81 mm. The diameter of the material to be held in the grip area is 120 mm. When the piston was opened to 115.92 mm, the grippers collided with each other. As shown in Figure 2, when the piston was approximately 94 mm open, it fully gripped the 120 mm diameter material. The length may vary slightly due to the rubber material in the grip area.

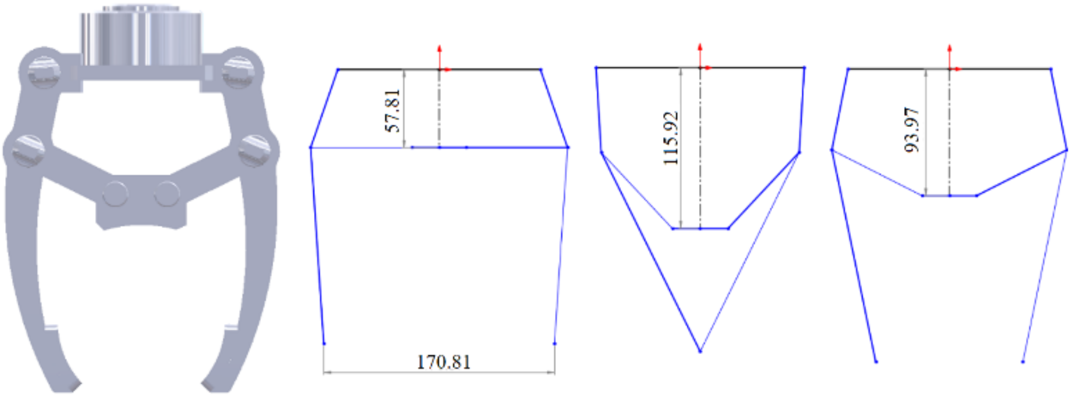

Figure 2. Gripper Motion Mechanism

An initial force must be applied to grasp the material. A pneumatic cylinder with a piston diameter of 44 mm was used to apply an initial force to hold the material. For this purpose, a pressure of 5 bar was applied, resulting in an initial force of approximately 760 N for the piston. This force, when divided among the two arms of the gripper, was 122.7 N per arm, as shown in the free body diagram in Figure 3. This force is further divided into vertical and horizontal components, exerting 91 and 82.3 N, respectively. The gripper's two arms move closer and further apart simultaneously during the piston's vertical movements.

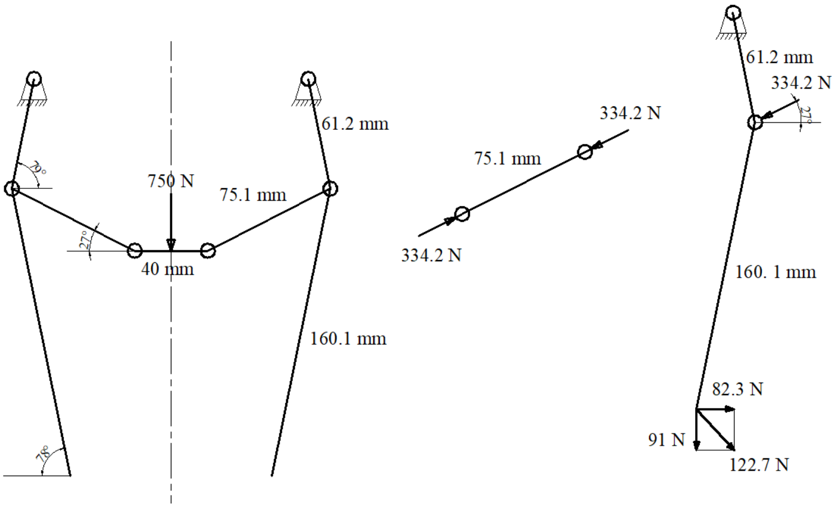

Figure 3. Free Body Diagram Showing the Forces Acting on the Gripper Arms

Figure 4 illustrates the boundary conditions applied to the gripper mechanism designed for a 500 kg load handling system. The following forces and constraints are applied:

Fixed Boundary Conditions: A fixed support is applied at the piston connection point to simulate the real-world attachment.

Piston Force: The gripper is actuated by a piston applying a total force of 750 N to the system.

Vertical Forces: Each arm of the gripper handles half of the 500 kg load (250 kg per gripper), resulting in a force of 2452.2 N. This force is divided between the two arms, leading to a vertical force of 1317.25 N per arm.

Horizontal Forces: The gripping action introduces a horizontal force of 82.3 N on each arm. This represents the lateral interaction with the cylindrical part being handled. The forces applied to the other two gripping surfaces were separately defined as vertical and horizontal components, as shown in Figure 4.

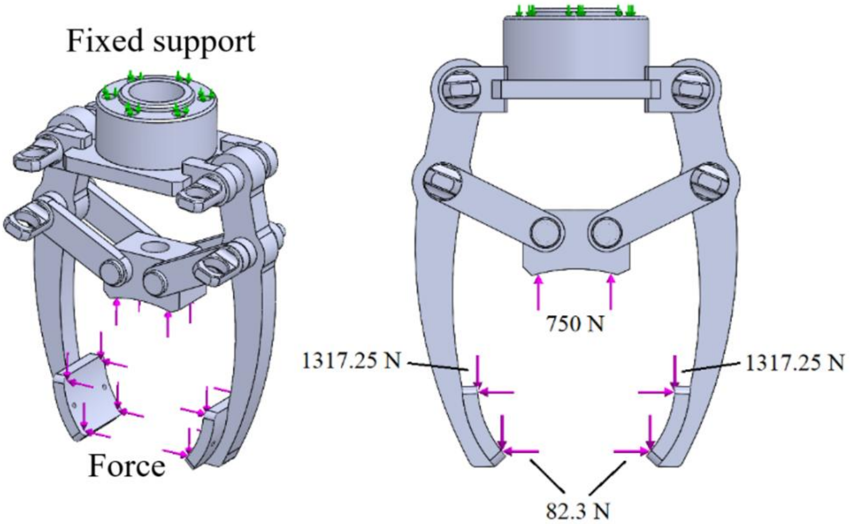

Figure 4. Boundary Conditions

Mesh Generation for Finite Element Analysis

This section details the mesh-generation process employed for the static strength analysis and topology optimization of the pneumatic gripper design. SolidWorks software was used to create high-quality meshes suitable for accurate finite element analysis (FEA). Figure 5a and Figure 5b show the mesh used for strength analysis and topology optimization, respectively.

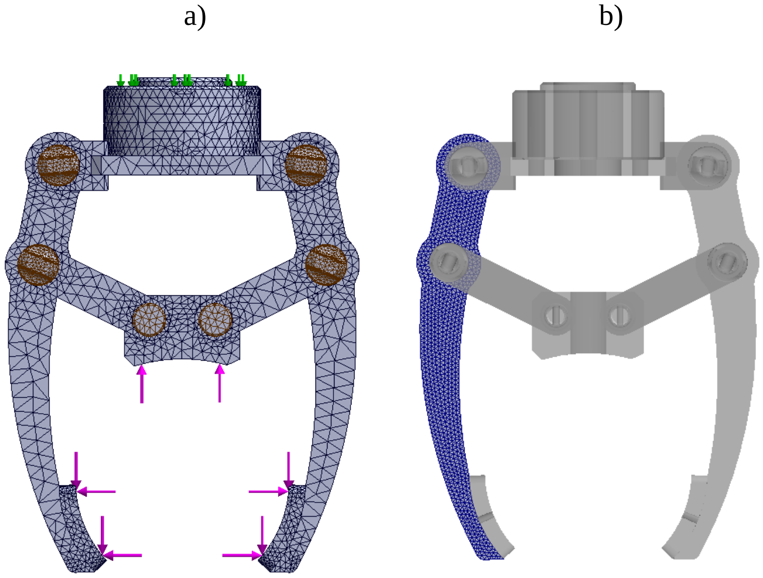

Figure 5. Mesh Structures a) Strength and b) Topology Analysis

A solid mesh was used for both analyses to ensure an accurate representation of the gripper's geometry and material behaviour. The static analysis employed a curvature-based mesh to capture the curvature variations in the gripper design. The topology optimization was performed using a blended curvature-based mesh. The proposed mesh combines curvature-based refinement with additional considerations to optimize the material distribution during the optimization process.

Mesh Quality and Refinement

Table 1 summarizes the key mesh statistics of both analyses. The mesh generation process ensured high-quality meshes for both analyses. The use of solid meshes and appropriate mesh refinement strategies facilitated an accurate representation of the gripper geometry and material behaviour. The finer mesh employed in the TO analysis matched the specific requirements of optimizing the material distribution. The minimal presence of distorted elements in both meshes ensured reliable results for static analysis and topology optimization.

Both analyses prioritize high-quality meshes with minimal distortion. This was achieved using 16 Jacobian points during element generation. The static analysis employed a mesh with a maximum element size of 11.091 mm and a minimum element size of 2.218 mm to balance the computational efficiency while capturing geometric details. The TO utilized a finer mesh than the static analysis, with a maximum element size of 2.644 mm and a minimum size of 1.586 mm, which were necessary to accurately capture the detailed material distribution patterns that emerged during the optimization process.

Table 1. Mesh Details

Property	**Static Analysis**	**Topology Optimization**
Mesh Type	Solid	Solid
Mesher	Curvature-based	Blended curvature-based
Mesh Quality	High/Draft	High
Maximum Aspect Ratio	43.885	3.267
Min Element Size (mm)	2.218	1.586
Total Elements	187743	49195
Maximum element size (mm)	11.091	2.644
Jacobian Points	16	16
Total Nodes	187035	74248
% Elements with Aspect Ratio > 10	0.0703%	0%
% Elements with Aspect Ratio < 3	95.7%	100%
Distorted Elements	0	0

RESULTS AND DISCUSSION

The static strength analysis of the gripper mechanism reveals a maximum von Mises stress of 105 MPa, which is well below the yield stress of the material (620.4 MPa, as shown in Figure 6. This indicates that the gripper can safely withstand the applied loads without exceeding the material yield point, thereby ensuring structural integrity during operation. Additionally, the gripper arms exhibit a displacement of approximately 0.402 mm at the point where the rubber pads are attached, as shown in Figure 7.

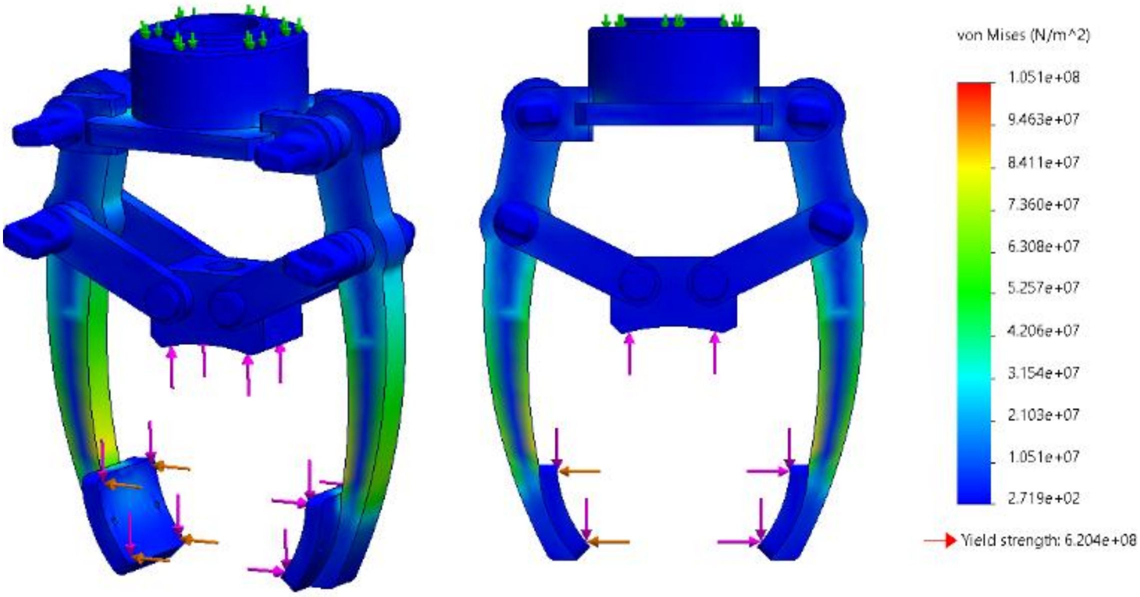

Figure 6. Von Mises Stress Distribution in the Gripper

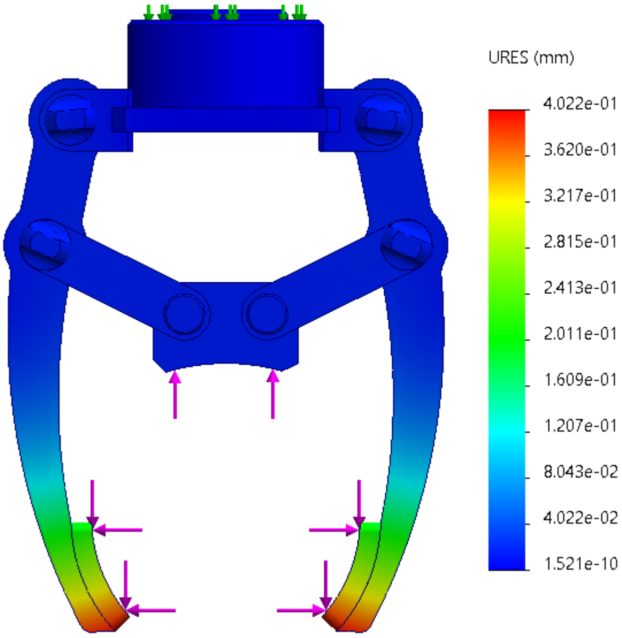

Figure 7. Displacement of the Gripper Arms

The finite element analysis reveals a safety factor of 5.16. The safety factor is calculated by dividing the material yield stress by the maximum von Mises stress experienced during operation. A safety factor greater than 1 indicates that the design can withstand the applied loads without exceeding the material yield point, thereby ensuring structural integrity. In this case, a safety factor of 5.16 provides a significant margin against failure, demonstrating the gripper's ability to safely handle the intended loads.

To further enhance the gripper's performance and efficiency, a topology optimization analysis is conducted. This optimization process redistributes the material within the gripper to minimize its overall mass while maintaining or improving the structural integrity. As illustrated in Figure 8, topology optimization successfully reduces the stress concentration in the gripper arm. The maximum von Mises stress increases slightly from 105 to 131.5 MPa. The observed insignificant increase in stress demonstrates the effectiveness of topology optimization in improving the gripper's structural performance.

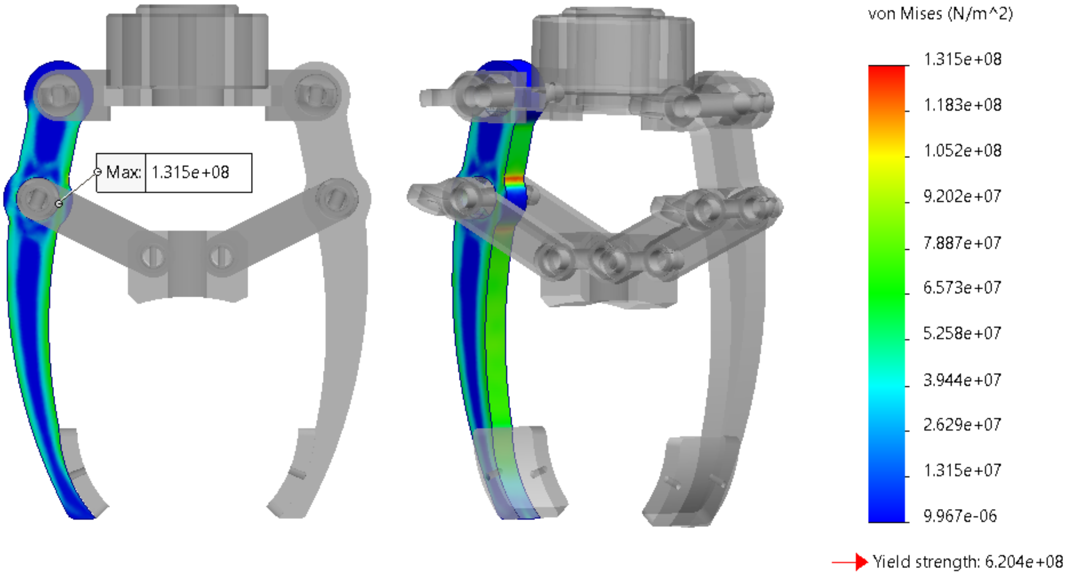

Figure 8. Topology Optimization Stress Distribution

Figure 9 shows the modified geometry of the gripper after topology optimization. This figure highlights the areas where material has been strategically removed to achieve the desired stress reduction without compromising structural integrity. The optimization process redistributes the material within the gripper focusing on creating a more efficient load path while minimizing the overall mass. The effectiveness of topology optimization can be further observed in Figure 10, which depicts the displacement experienced by the gripper arm in the designated region at the end of the gripper arms. While the optimization process primarily aimed to reduce stress concentrations, it also yields a displacement of 0.446 mm at this specific location. This result demonstrates the ability of topology optimization to simultaneously improve both the strength and displacement characteristics of gripper designs.

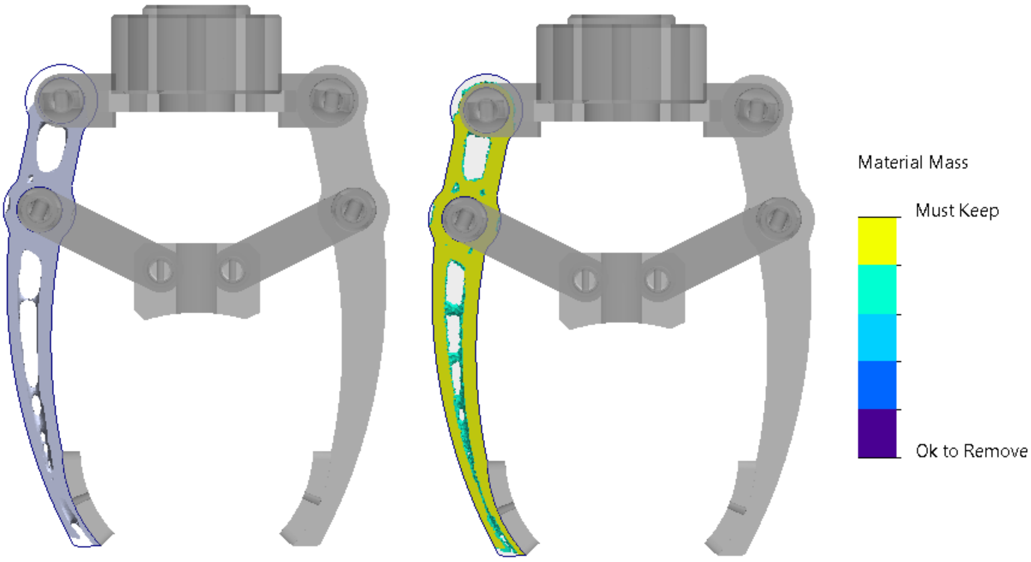

Figure 9. Material Mass Distribution after Topology Optimization

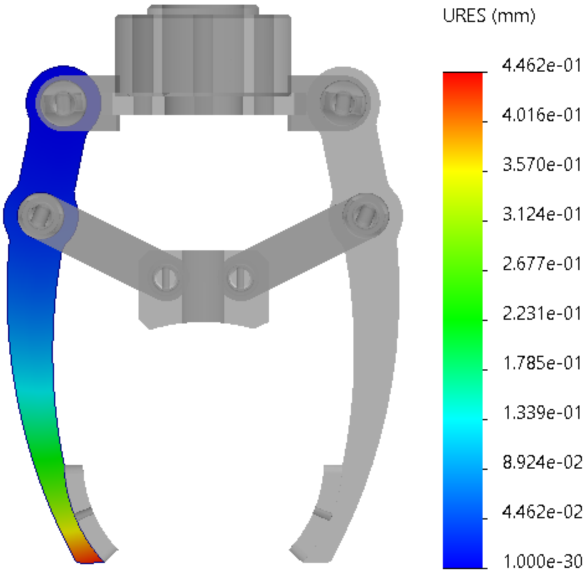

Figure 10. Displacement Distribution after Topology Optimization

The initial FEA analysis of the gripper mechanism under a 5 bar pressure demonstrates a safety factor of 5.16, confirming that the design could safely handle the applied loads. However, to improve the overall efficiency of the system, a topology optimization process is implemented to reduce the mass of the gripper while maintaining its structural integrity. As a result of this optimization, the gripper's mass is reduced by 35%, significantly lightening the overall structure. After topology optimization, the safety factor of the gripper remains at a satisfactory level of 4.72, indicating that the design continues to meet the safety standards. Table 1 summarizes the critical parameters of the initial and topology-optimized gripper designs. Notably, the optimized design achieves a higher maximum von Mises stress of 131.5 MPa than the initial design (105 MPa, suggesting a slight increase in the stress concentration. Additionally, this optimization comes with a trade-off the optimized design exhibits a marginally higher displacement of 0.446 mm compared to the initial design of 0.402 mm.

Although the safety factor shows a minor decrease from 5.16 in the initial design to 4.72 in the optimized design, these changes underscore the balance between weight reduction and structural performance. Despite these variations, the overall performance improvement and material savings validate the effectiveness of topology optimization in enhancing the gripper’s design. The increase in stress concentrations after optimization is within acceptable limits, ensuring that the gripper can continue to handle the necessary loads without compromising its structural integrity. These findings highlight the effectiveness of combining FEA and topology optimization to achieve more efficient designs while balancing safety and performance requirements.

The SF/M ratio (Equation (1)), defined as the ratio of the safety factor to the mass of the gripper, was calculated for both the initial and optimized designs. For the initial design, the SF/M ratio was 1.0, serving as the baseline. After optimization, the SF/M ratio improved by 42%, reaching a value of 1.42. This indicates that the optimized design achieved a better balance between safety and mass, demonstrating a significant improvement in structural efficiency.

Table 2. Comparison of Initial and Optimized Design Parameters

Parameter	Initial Design	Optimized Design
Maximum von Mises Stress (MPa)	105	131.5
Displacement (mm)	0.402	0.446
Safety Factor	5.16	4.72
Mass Reduction	-	%35
Gripper Mass (kg)	23.3	15.1

CONCLUSION

This study investigates the structural performance of a pneumatic gripper mechanism designed for a 500 kg material handling system using finite element analysis (FEA) and topology optimization. The FEA results demonstrate that the initial gripper design could safely withstand the applied loads with a maximum von Mises stress of 105 MPa, which is well below the material yield stress of 620 MPa. This ensures structural integrity during operation with a safety factor of 5.16.

The topology optimization further improves the gripper design by reducing the stress concentration. The optimized design achieves a maximum von Mises stress of 131.5 MPa. However, a slight trade-off exists between stress reduction and displacement. The optimized design exhibits a marginally higher displacement of 0.446 mm compared to the initial design’s displacement of 0.402 mm.

The initial design has an SF/M ratio of 1.0, while the optimized design achieves a ratio of 1.42, demonstrating a 42% improvement in structural efficiency. This indicates a better balance between safety and mass reduction, with the optimized design showing an improvement in overall performance.

This study demonstrates the effectiveness of FEA and topology optimization in optimizing gripper designs for material handling applications. By optimizing the material distribution, gripper performance can be improved while minimizing weight. In this case, the optimized design achieves a stress reduction while maintaining a sufficient safety factor, even with a slight increase in displacement. These improvements ultimately enhance the functionality and efficiency of robotic and mechanical gripping systems in the automotive industry and beyond.

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