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ORIGINAL ARTICLE

A Note on Redesign Material Substitution and Topology Optimization in a Lightweight Robotic Gripper

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Abstract

The gripper is required because it is the portion of the robot that makes direct contact with the object being grasped. It should weigh as little as possible without compromising functionality or its performance. This study aims to reconsider the construction of a lightweight robotic gripper by modifying the gripper's materials and topology. Using the finite element (FE) method, several types of gripper materials were evaluated for static stress. On the basis of the results of the FE analysis, the optimal material candidate was chosen using the weighted objective method. Using the Fusion 360 software, the topology of the selected material was then optimized in an effort to achieve the 40% weight reduction's objective. In addition, the suggested optimized geometry is then fine-tuned so that it can be manufactured as efficiently as possible. The final step in the validation of the robotic gripper's design was stress static analysis. The revised gripper design has a mass of 0.08 kg, a reduction of 94% from the original mass, and a safety factor of 3.67%, which satisfies the desired level of performance for the robotic gripper. Utilizing different materials and optimizing the gripper's topology can significantly reduce the overall mass of a robotic gripper.

Keywords: Material substitution, Robotic gripper, Stress analysis, Topology optimization, Lightweight design

Introduction

The development of improved robotic grippers has been frequently studied since the beginning of industrial automation. Grippers need to be capable of holding, lifting, and manipulating objects without damage, and their performance characteristics depend on the objects they interact with. Hasan et al. (2019) developed a fabric-based lightweight robotic gripper that is flexible, lightweight, completely foldable, and has a high payload capacity. Grippers are essential for performing tasks requiring grasping and important considerations when choosing a gripper include the speed of manipulation, shape and weight of the object, and other relevant characteristics. Topology optimization and material substitution are methods for reducing the weight of a component, and lightweight robotic arms are being designed with materials such as hollow sphere composite, carbon fibre reinforced plastic, and aluminium alloy. The use of lightweight robotic arms is increasing in various industries such as agriculture, industry, and space exploration due to energy efficiency and productivity requirements. The 2-finger or 2-claw grippers are regarded as the most fundamental types of robot grippers. This is due to the fact that they are simple to use and manufacture, as well as cost-effective and economical. Additionally, they are suitable for a wide variety of applications in the industrial sector. These types of robots are capable of performing a variety of tasks, including assembly, pick and place, and simple manipulations. There are a variety of criteria that can be used to categorize grippers, including their configuration, mode of operation, field of application, size, and level of stiffness (Samadikhoshkho et al., 2019).

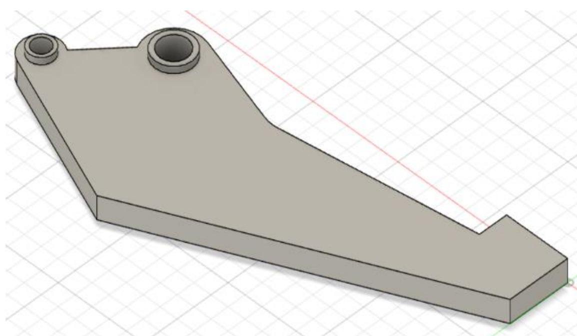
Topology optimization is a type of structural optimization involving the distribution of available materials in the design space to achieve the desired performance. The design space is segmented into discrete elements referred to as isotropic solid microstructures using finite element methods. This segmentation makes it possible to evaluate various functions, models, and equations using a computer and numerical methods. Topology optimization is used to achieve the goal of improving upon previously obtained results by revealing which mesh elements are voids and which ones are solids. The primary objective is to lower the body mass index while maintaining or enhancing strength, resulting in a lighter and less expensive product. Previous studies have demonstrated the effectiveness of topology optimization in reducing weight, such as the steel brake pedal for an automobile (Sudin et al., 2014), the connecting rod (Yildiz et al., 2019), the engine bracket (Ramli et al., 2019), and the spur gear (Kulangara et al., 2019). All of these studies reported significant weight loss while still satisfying the performance requirements. For example, Manikandan et al. (2018) improved the motorcycle frame's weight from 3.065 kg to 2.215 kg without affecting its performance.

Material substitution is an alternative method to topology optimization for reducing the weight of a component. This method reduces the weight of a component by using lighter materials such as high-strength steel, aluminium, magnesium, lightweight composites, and plastics. Lightening the load of a road vehicle is done with the goal of improving its efficiency in terms of fuel consumption. The other reasons are so as to achieve better performance and so as to have a greater load carrying capacity. There have been numerous research reports published on the topic of replacing heavy materials like metal with lighter materials like composites in order to cut weight. Mansor et al. (2014) utilized kenaf fibre polymer composites for the manufacturing of automotive parking brake levers as well as automotive spoilers (Mansor et al., 2015). Mastura et al. (2018) redesigned the antiroll bar found in automobiles by employing a natural fibre reinforced composite material in their construction. While this is going on in the robotics industry, lightweight robotic arms are currently being designed with hollow sphere composite (HSC), carbon fibre reinforced plastic (CFRP), and aluminium alloy (AA) as some of the lightest materials available. Lightweight robotic arms are seeing increased use across a variety of industries, including agriculture, industry, the service sector, and even space exploration, in order to meet the requirements of energy efficiency and productivity. The term "lightweight robotic arm" refers to the fact that it is necessary to decrease the weight of the arms in order to fulfil certain conditions. The advancement of material science has led to the creation of a variety of lightweight materials that are both highly rigid and have a low overall density. Cheng et al. (2010) developed a fully plastic micro robot (FPMR) by combining cross-linked liquid-crystalline polymers and polyethylene films. In a similar fashion, flexible plastic was used in the fabrication of an underwater robot (UWR) in order to lessen both the weight of the robot and the force that was generated by the pressure difference between the inside and the outside of the robot (Yin et al., 2019). Both the FPMR and the UWR make use of plastic materials, and while these materials have a high stiffness-to-mass ratio, the absolute strength and stiffness of these plastic materials is quite low. The flanges of the robotic arms were designed and manufactured by (Hagenah et al., 2013) using titanium, and the joint housing was manufactured using nanocrystalline aluminium alloy. Both of these materials have the ability to achieve a lighter structure than their conventional casting counterparts. This review sheds light on the recent research that has been conducted in the field of the design and development of high performance robotic grippers. Specifically, this review focuses on the research that has been conducted in the last few years. As a consequence of this, the purpose of this study is to investigate the potential for rapidly multiplying the weight reduction of the gripper through the utilization of a combined method. This method includes the combination of material substitution and topology optimization based on the computational analysis platform.

Materials and Methods

Static Stress Analysis of Robotic Gripper and Material Selection

The Fusion 360 basic training simulation was used to create the 3D model of the robotic gripper. The initial gripper design is shown in **Figure 1** along with its characteristics. The initial mass of the steel object is 136.74g, and it has a volume of 17419.16 mm^3. To make a gripper lighter with at least a 3.0 safety factor, it must be redesigned from an existing model.



Area	8941.74 mm^2
Density	0.0079 g/mm^3
Mass	136.74 g
Volume	17419.16 mm^3
Physical Material	Steel

Figure 1. Original design of robotic gripper and its properties

For the purpose of carrying out the stress test, Fusion 360 was utilized. The purpose of this analysis is to determine the safety factor and the amount of displacement that the gripper experiences for a variety of different materials. The constraint was placed on the gripper's holes at the same time. Pins were the type of constraints that were applied. The tangential direction was freed up so that the gripper could rotate about its axis of rotation. On the other hand, the radial and axial directions were locked in place. On the surface of the end of the gripper, a normal force measuring 5 N was applied. During the course of the study, a wide range of materials, such as steel, aluminium, PC/ABS plastic, and nylon 6, were evaluated. The illustrative results of the computational stress analysis are displayed in **Figure 2**.

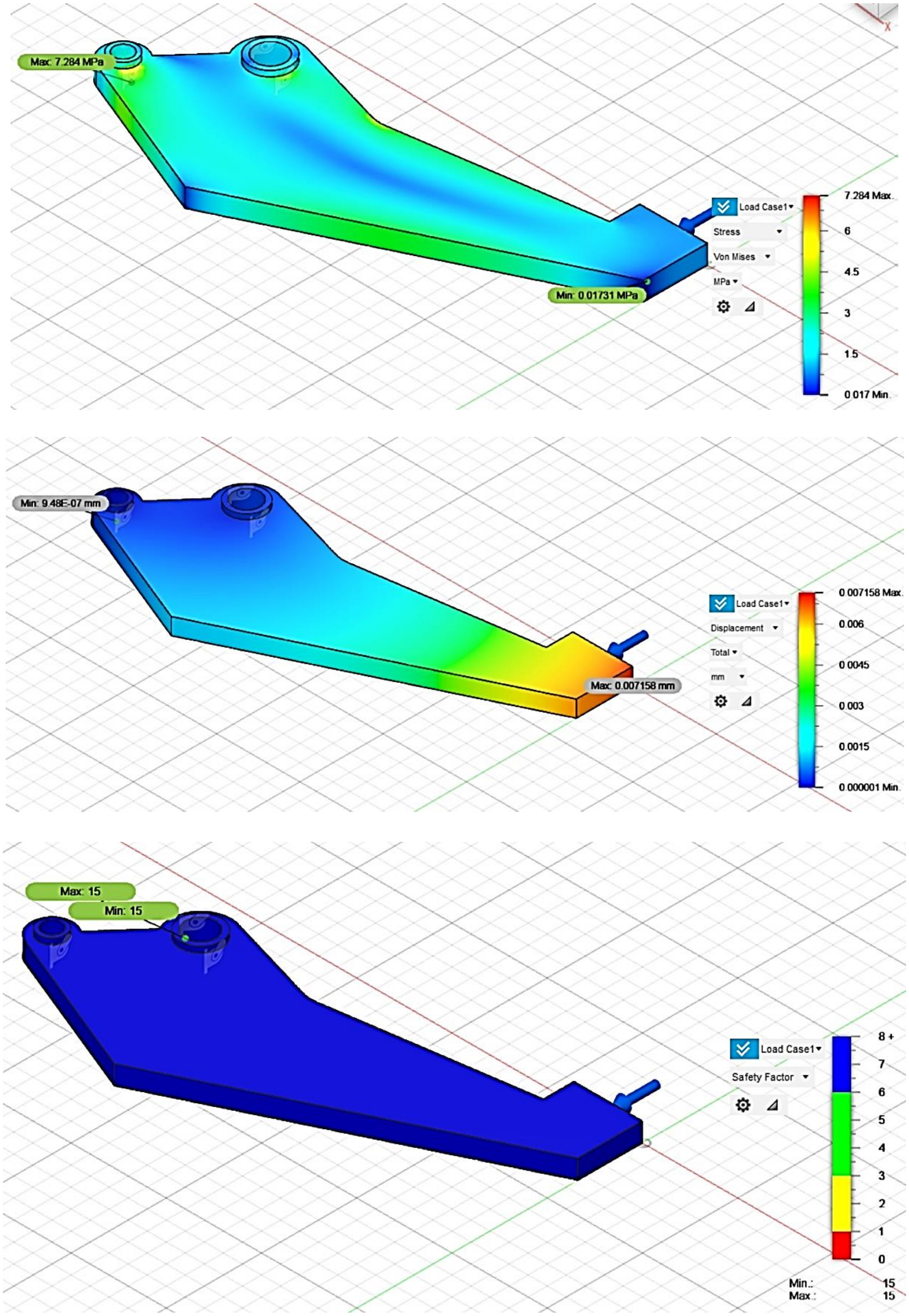


Figure 2. (a) Computational stress analysis (b) displacement and (c) safety factor of robotic gripper for steel material

The safety factor and the gripper displacement are the outputs that are required from the stress analysis for this study. The first step in the procedure for selecting the material is to establish the weight factor for the selection criteria. The safety factor, displacement, and mass of the gripper were evaluated during the selection process. These three characteristics each had a weight factor of 5, 3, and 4, respectively. The designer decided with a reasonable amount of self-assurance on the weight factor that would be assigned to the selection criteria. Using a scale from 1 to 5, a weight factor is decided upon for each of the criteria. For the purpose of this investigation, the weight factor for mass is set at 4, reflecting the fact that reducing it is the primary objective of this redesign. The safety factor is also set at 5, reflecting the fact that increasing it is of equal importance for the gripper redesign. However, the weight factor for displacement is 3, and it is regarded as having a significance that is somewhere in the middle. The results of the computational stress analysis performed on the various materials, which are tabulated in **Table 1**, were used in the process of selecting the best material for the gripper. This was done using the information presented in the table.

Table 2 presents an outline of the results obtained from the examination of various materials for use in robotic grippers. In order to arrive at the final product, the designer first had to determine the rating for each material based on a particular selection criterion. Next, the designer multiplied that rating by the weight factor. When these three components are added together, a final score for the material can be calculated. When it comes to the safety factor, the absolute bare minimum that is required is a safety factor of 3. Each of the materials has, as evidenced by the results of the FE, attained the minimum safety factor that was mandated to do so. Even though one of the materials has a higher safety factor than the required minimum safety factor, this does not necessarily mean that it will be given a higher rating. In the realm of engineering, a design that features a high safety factor is considered to be "over-designed," and as a consequence, it is possible to work around the design in order to achieve cost savings.

The ratings of aluminium, PC/ABS, and Nylon6 are respectively 2, 4, and 3, and this is a direct consequence of this. Materials with lower mass and displacement are rated higher, so lightweight materials with low displacement are preferred. Since higher ratings are given to materials with lower mass and displacement.

Table 1. Comparison of computational results of gripper for different materials

Material	Volume (mm^3)	Density (g/mm^3)	Mass (g)	Stress (MPa)	Displacement (mm)	Safety factor
Steel	17419.16	$7.85x10^{-3}$	136.74	7.28	0.07	15.00
Aluminum	17419.16	$2.70x10^{-3}$	47.03	7.13	0.02	15.00
PC/ABS plastic	17419.16	$1.10x10^{-3}$	19.16	6.74	0.54	8.07
Nylon6	17419.16	$1.12x10^{-3}$	19.50	7.24	0.55	9.72

Table 2. Matrix evaluation of the robotic gripper used to select the best material

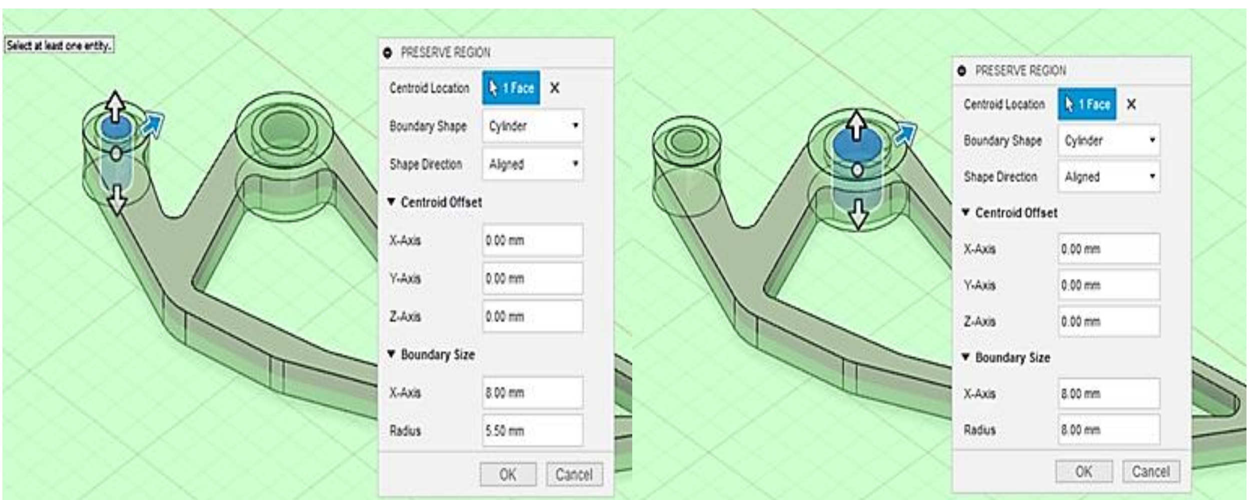
No.	Criteria	Weight factor	Rating			Weight factor x rating		
			Aluminium	PC/ABS	Nylon6	Aluminium	PC/ABS	Nylon6
1	Safety factor	5	2	4	3	10	20	15
2	Displacement	3	5	2	2	15	6	6
3	Mass	4	1	5	4	4	20	16
	Score					29	46	37

Topology Optimization of Robotic Gripper

The purpose of topology optimization is to distribute materials in the design space in such a way that they are subjected to loads and constraints in the most effective manner possible, with the end goal of increasing the part's overall performance. In contrast, the non-design space refers to the volume in which the material is kept at its original concentration of 100%. The design space refers to the volume in which the material is optimally distributed.

Figure 3 shows the non-design spaces, which are the two holes with a material preserve of 5.5 mm and 8 mm around the smaller hole and the larger hole, respectively. The goal of any optimization problem is to minimize or maximize a given response while adhering to a specified set of constraints. When it comes to optimizing the topology of robotic grippers, the goal is to achieve the highest possible level of stiffness while keeping the target value at about 40 %. In the normal direction, a load of 5 N was applied to the gripper end, and pin-type constraints were applied to both holes.

The radial and axial directions were immovable, but the tangential direction was free to allow for rotational movement of the gripper. The top surface of the gripper was chosen as the location to create the symmetrical plane in order to guarantee that the optimized gripper maintains the same level of symmetry throughout its thickness as the first gripper.



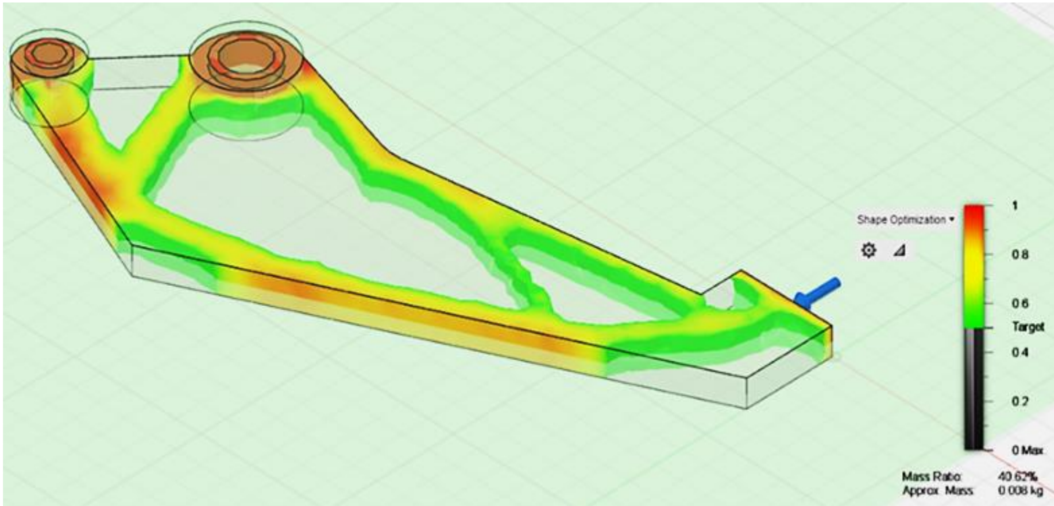
(a) (b)

Figure 3. Preserve area for the (a) small and (b) large hole

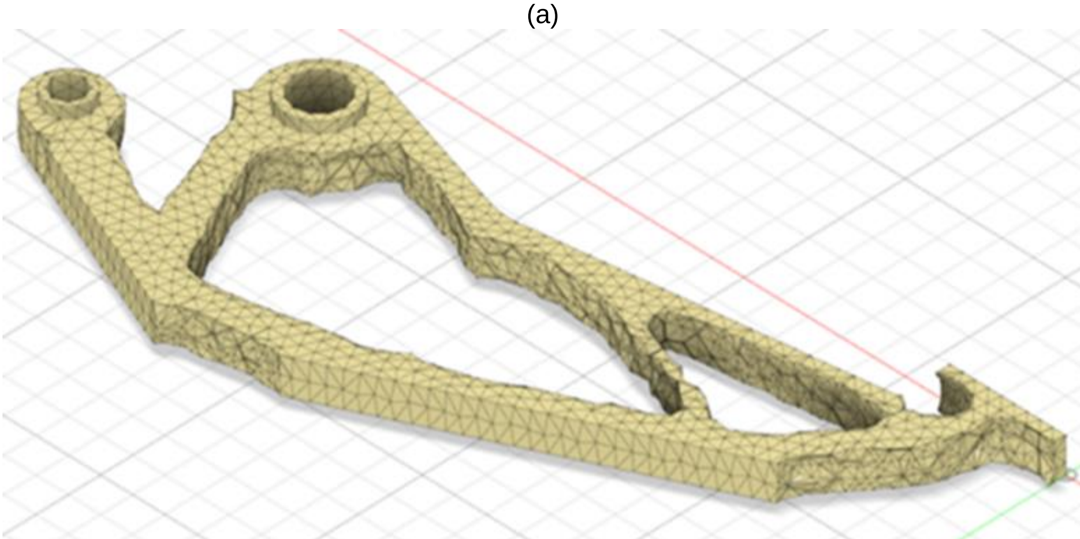
PC/ABS plastics were selected as the material for the gripper for the topology optimization based on the findings of the finite element analysis and the matrix evaluation method. This decision was made to ensure that the gripper would have the best possible performance.

After the topology optimization was complete, the result was exported to the design workspace, where it was used to create a mesh object that would serve as a template for the modification of the original geometry while the design workspace was operating in sketch environment mode.

This modification is essential to ensure that the final design can be manufactured successfully. **Figure 4** depicts the gripper in its final form before undergoing the aforementioned modifications.



(a)



(b)

Figure 4. (a) topology optimized design of gripper, (b) meshed topology optimized of gripper

Design Verification

Following the modification, a topologically optimized robotic gripper design was subjected to another static stress analysis. This was done to ensure the system's proper operation. The boundary conditions of this analysis accurately reflect the stress analysis performed on the original gripper. The gripper, which was previously made of steel, will now be made of PC/ABS plastic. This verification ensures that the gripper's final safety factor is at least 3.0.

Result and Discussion

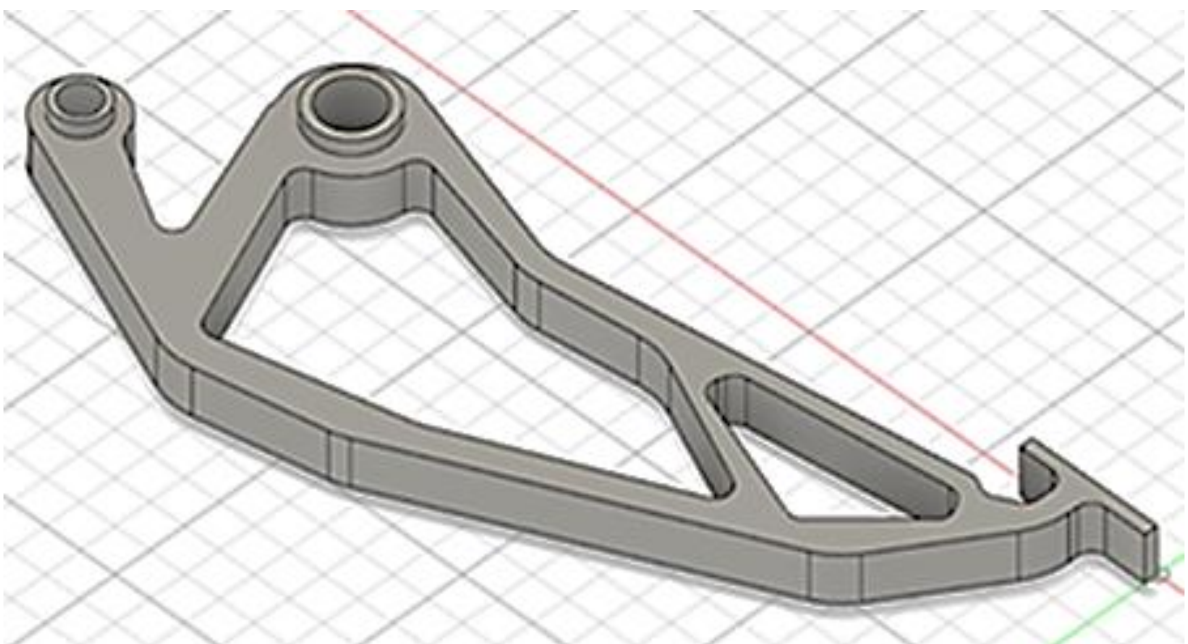
Table 3 contains a summary of the properties of the gripper based on the various mass reduction strategies that were utilized in the redesign of the robotic gripper. The initial creation of the gripper yielded a weight of 137g, and the material steel was used in its construction. On the basis of the findings of a stress analysis carried out on four distinct materials and the matrix evaluation technique, the PC/ABS plastic material was selected as the new material for the robotic gripper.

It was discovered that using lightweight materials leads to a reduction in mass of 86%, while using a topology optimization approach leads to a reduction in mass of 59%. Neither of these approaches sacrifices performance.

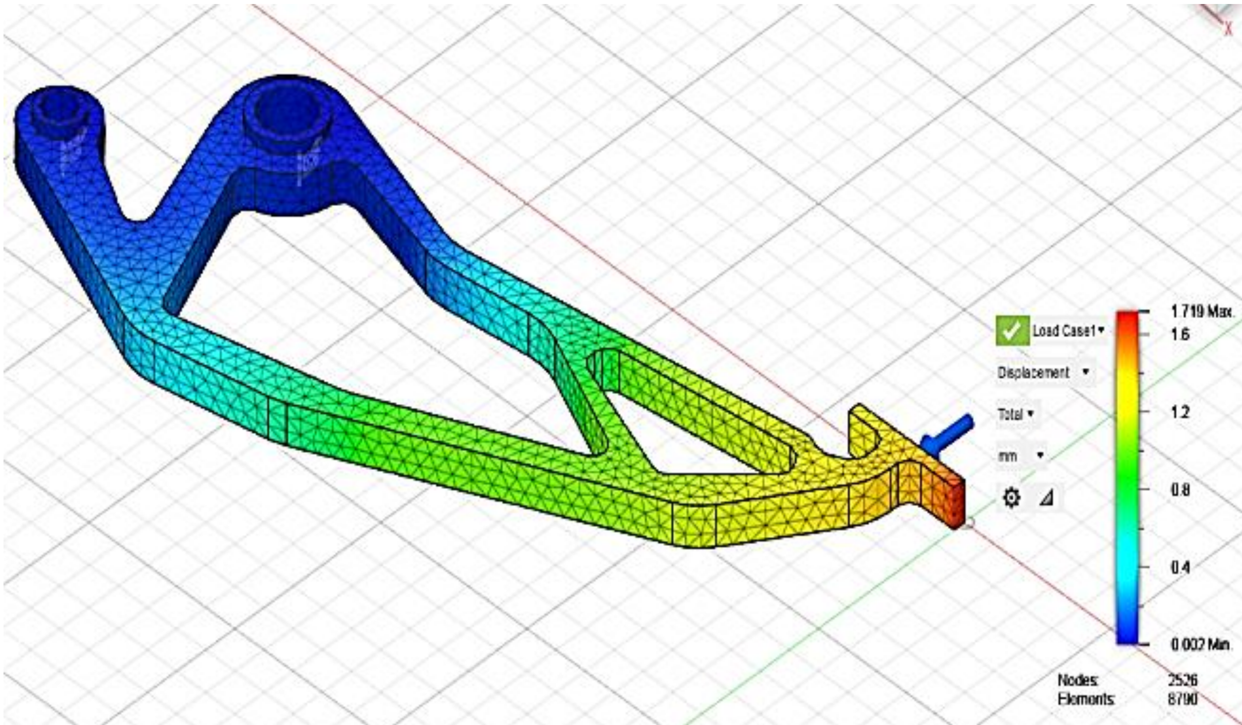
The final design of the robotic gripper was able to achieve a mass reduction of 94% when compared to its initial mass by making use of material substitution and topology optimization. The final design has a mass of 0.008 kg. Although the final safety factor is 3.70% lower than the initial design, it still meets the minimum requirement of 3.0, and the displacement is considered acceptable since it does not reach the plastic region of the material. Figure 5 illustrates the final design of the gripper and the results of the FE calculations for safety factor and displacement.

Table 3. Summary of properties of gripper based on different approach for mass reduction

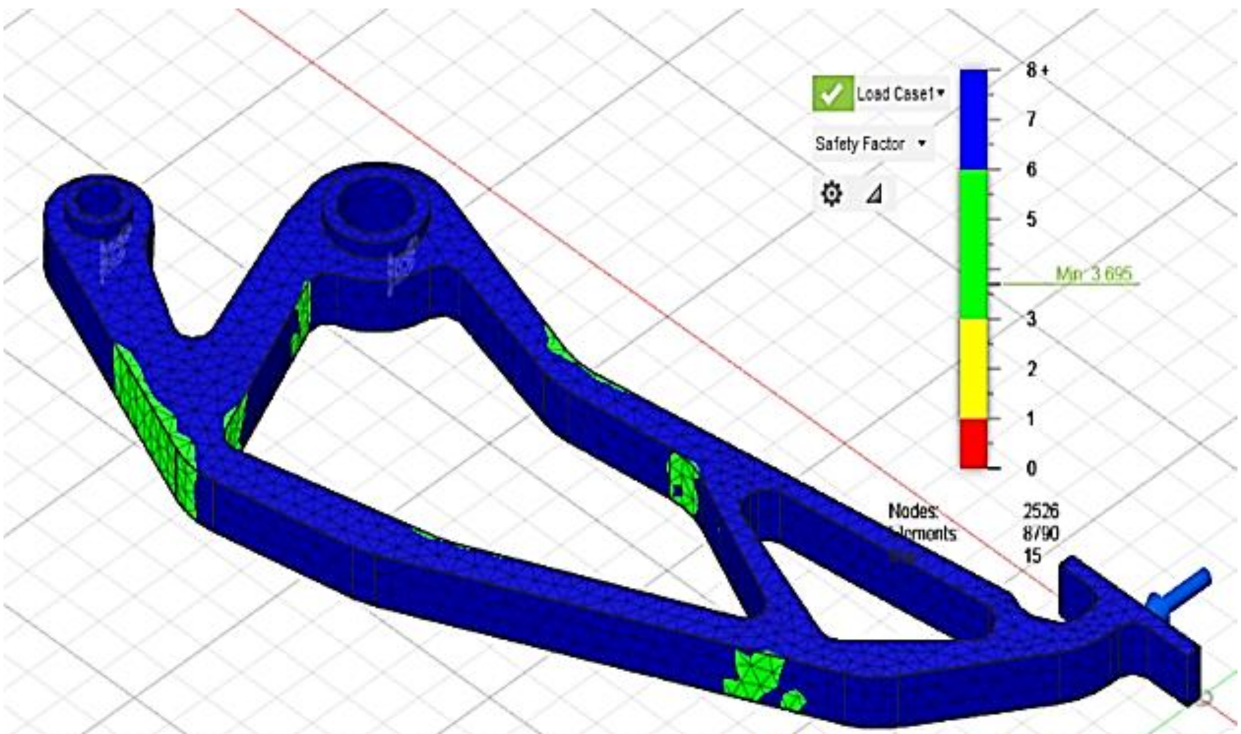
Property	**Original design**	**Weight reduction method**		
		Material substitution	**Topology optimization**	**Topology optimization and material substitution**
Material	**Steel**	**PC/ABS plastic**	**Steel**	**PC/ABS plastic**
Mass (g)	136.74	19.16	55.68	8
% of mass reduction	-	86%	59%	94%
Safety factor	15.00	8.07	13.7	3.70
Displacement (mm)	0.07	0.54	0.02	1.72
Volume (mm^3)	**17419.16**	**17419.16**	**7079.92**	**7079.92**



(a)



(b)



(c)

Figure 5. (a) Final design of gripper (b) FE result of displacement (c) FE result of safety factor of the final robotic gripper

Conclusion

It is possible to reduce the weight of a component in a limited number of ways. By replacing the current metal material with a lighter material, we can achieve the weight reduction objective. In the meantime, the topology optimization that attempts to distribute material within the design domain by assigning material to the location where it is required and removing material from the low-stress area where it is not required also results in a substantial reduction in the component's weight.

By combining these two techniques, as was done in this study, it is possible to multiply the weight reduction of a component without compromising its performance. In this study, weight reduction is up to 86% with material substitution, 59% with topology optimization, and up to 94% when these two techniques are combined. This strategy may provide a fresh perspective on weight reduction techniques across engineering disciplines.

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