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Topology Optimization of a Robot Gripper with nTopology

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Abstract

The robot gripper works analogously to the human hand, being the end effector of a robotic mechanism and acting as a bridge between the robot and the environment. A topology optimized gripper can be fully functional while allowing weight reduction. In this paper, the topology optimization of a 316L-SS four-clamp gripper capable of withstanding a 2 N load was conducted using the nTopology software. Fusion360 static stress analysis showed a reduction of 43% in weight, keeping the safety factor above 3, and leading to a displacement of 0,0067 mm. Finally, the maximum induced stress was shown not to cause permanent deformation of the clamp since it was observed to be inferior to the yield strength of 316L-SS.

1. Introduction

One of the key factors in determining the ultimate application of robots is its gripper, which consists of the end effector of a robotic mechanism and acts as the mechanical interface between the robot and the surrounding environment, represented in Figure 1.

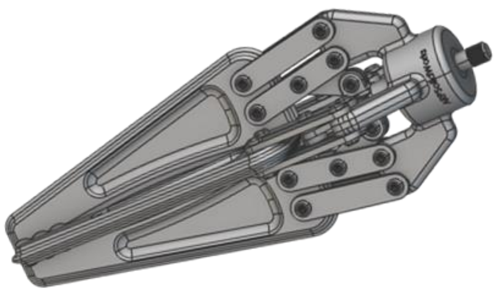


Figure 1: CAD model representation of a gripper (Pérez, 2016)

Due to this, the gripper is analogous to a human hand, allowing one to pick up, move, and position any object. One of the main fields of applications for grippers involves dangerous and hazardous tasks, such as high-temperature welding, radioactive material handling, disarming bombs, and mines, or complex and challenging tasks, such as medical surgeries. The type of application required also sets constraints for the design of the gripper, which can be customized to respond to certain kinds of hazardous or complex tasks (Raghav, Kumar, and Senge 2012; Datta, Pradhan, and Bhattacharya 2016; Sugavaneswaran, Rajesh, and Sathishkumar 2020; Mata et al. 2023).

On the other hand, topological optimization (TO) is a mathematical approach based on Finite Element Analysis (FEA) that leads to determining the parts of a given component that truly contribute to a given application. Regions where material can be removed and where material should be added are determined by TO. Thus, optimizing the component's design is possible, assuring it complies with certain restrictions and limit boundaries while allowing the intended functionality to be achieved with the lowest possible material consumption and ensuring a uniform service load distribution. Topological optimization leads to light-weighting, stiffness optimization for maximum volume, and cross-sectional area decreasing where the load is applied (Rosinha et al. 2015; Gaudillière et al. 2019; Ananthasuresh 2008; Oliveira et al. 2023).

The global problem of topology optimization is to determine the material distribution that allows the minimization of an objective function, F. This objective must comply with a volume constraint, G0 ≤ 0, and probably to N other constraints Gi ≤ 0, i = 1 ...N, while the material distribution is defined by the density variable ρ(x), which can either be 0 (void) or 1 (solid material), at any point of the design domain. Through a mathematical approach, the topology optimization problem can be written as (Sigmund and Maute 2013; Ananthasuresh 2008; Sugavaneswaran, Rajesh, and Sathishkumar 2020):

$$\begin{cases} \min\limits_{\rho}: \; F = F(u(\rho),\rho) = \displaystyle\int_{\Omega} f(u(\rho),\rho)dV \\ s.t.: \; G_0(\rho) = \displaystyle\int_{\Omega} \rho(x)dV - V_0 \leq 0 \\ \quad : \; G_i(u(\rho),\rho) \leq 0, j = 1, \dots, N \\ \quad : \; \rho(x) = 0 \; or \; 1, \forall x \in \Omega \end{cases} \tag{1}$$

As a result, topology optimization outputs usually present organic forms and complex shapes, which will pose a difficulty in manufacturability, especially when considering conventional manufacturing processes. Due to this, the production of optimized components resorts to additive manufacturing (AM), which allows high geometry freedom, reducing the constraints faced during conventional production. AM is a technology in which a three-dimensional component is built from a CAD model, usually layer upon layer. It was initially intended for prototyping but is currently employed in the creation of functional and structural components with complex geometry or customized structures while allowing a reduction of weight. These are a few of the main advantages associated with the AM techniques and the key ones linked to the needs to be fulfilled for the present component. Within the AM processes, PBF (powder bed fusion), SLM (selective laser melting), SLS (selective laser sintering), and FFF (fused filament fabrication) are amongst the most used ones. To select the adequate process for each application, one must consider the intended requirements, either within the mechanical, manufacturing, or aesthetic levels, and financial aspects. Subsequently, different process parameters and feedstock variables need to be studied and optimized to build and obtain the planned component with the intended requirements regarding design and mechanical properties (Gorsse et al. 2017; DebRoy et al. 2018; Bedmar et al. 2022; Zhang and Liou 2021; Sugavaneswaran, Rajesh, and Sathishkumar 2020; Maia et al. 2023; Oliveira et al. 2023).

As some of the features result from the topology optimization, laser powder bed fusion (LPBF) is the adequate process to build the final optimized gripper. This process resorts to a powder feedstock spread over as a thin powder bed layer, which is selectively melted by a laser beam, allowing the construction of the component layer by layer while under the protection of an inert atmosphere (King et al. 2015; Khairallah et al. 2016).

Hence, this project aims for the topology optimization of a robot gripper, as close as possible to the functionality of a human hand. Therefore, a gripper with four clamps was topologically optimized with a target of withstanding a load of 20 N, resorting to the nTopology software. Subsequently, simulations to test the mechanical response of the clamps were carried out using Fusion360.

2. Materials and Methods

2.1. Materials

The selected material for the clamps for posterior topology optimization and simulation is the AISI 316L stainless steel (316L-SS), widely used in many commercial applications requiring corrosion resistance properties in numerous modern industries. This stainless-steel grade exhibits extremely high corrosion and oxidation resistance, high strength, biocompatibility, and good wear resistance and ductility, which justifies its high and wide applicability. The wear, corrosion, and oxidation properties determine 316L-SS as a good material for gripper clamps, as it grants stability and durability to be employed in a reliable periods while being able to be used in corrosion applications. The biocompatibility allows 316L-SS to be selected for grippers in biotechnical fields, as it can also withstand most chemical sterilizing and cleaning agents (Biermann et al. 2022; Kazemipour et al. 2019; Hosseini et al. 2022). The typical chemical composition of the powders of 316L-SS manufactured through laser powder bed fusion is presented in Table 1.

Element	*C*	*P*	*Si*	*Ni*	*Mn*	*S*	*Cr*	*Mo*	*Fe*
wt.%	*0.03*	*0.02*	*0.75*	*14.00*	*2.00*	*0.01*	*18.00*	*2.62*	*Bal.*

Table 1: Typical composition of 316L metallic powders for LPBF, adapted from (Ronneberg, Davies, and Hooper 2020)

2.2. CAD Model

The CAD model used for the optimization was a four-claw gripper (Figure 1) found on GrabCAD, an online free CAD library owned by Stratasys. The main dimensions of the claw used are represented in Figure 2.

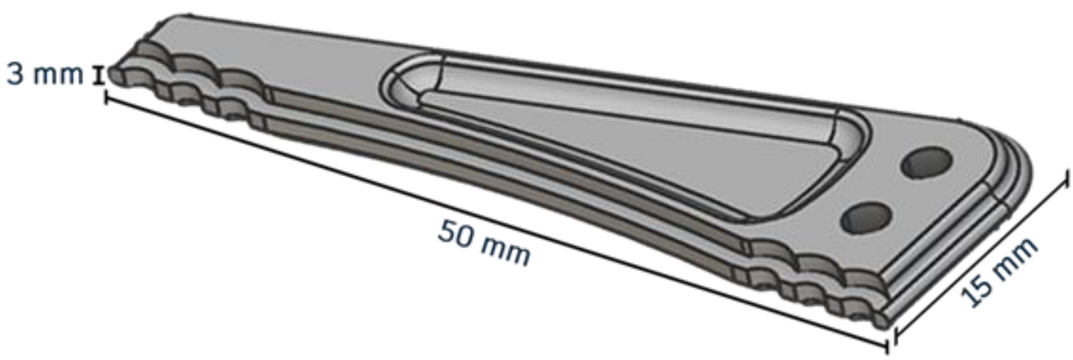


Figure 2: Gripper claw and dimensions (Pérez 2016).

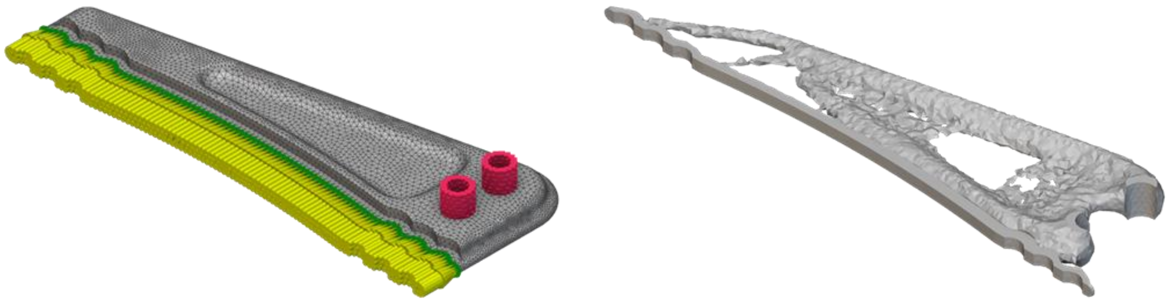
2.3. Optimization Procedure and Simulation

To optimize the gripper, the model was uploaded into nTopology, where one of the claws was isolated, following the subsequent steps only on this claw. Firstly, the isolated claw was meshed, using triangular elements to define the component's surface and remeshed to eliminate all mesh-related defects. A mesh volume was created to delineate the claw further, obtaining a solid tridimensional mesh that also defines its interior. Afterward, a finite element (FE) mesh was created and associated with the material attributes, selecting AISI 316L stainless steel, which led to a finite element model.

The model was uploaded to Fusion360 to undergo static analysis simulation and verify if the obtained design could withstand the 20 N load, which corresponds to nearly 2 kg. The displacement restraints and load application surfaces were selected to do this, those previously mentioned for the TO. These simulations are especially relevant to anticipate the mechanical response of the components and alter their design to adjust the mechanical properties, if required, before production, which avoids wasting resources on a non-viable component. However, these simulations are not a substitute for further and posterior mechanical tests that this component must undergo, highlighting that the clamp should be submitted to fatigue testing before commercialization.

3. Results

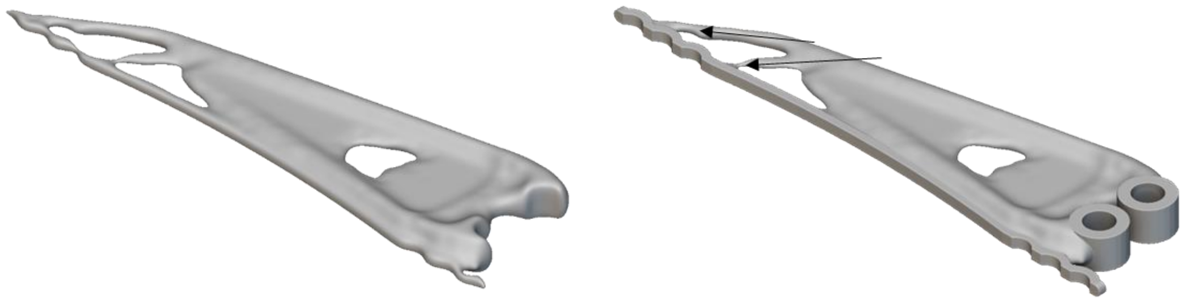
After creating the FE model, it was possible to proceed with the topological optimization. For this, boundary conditions were selected, as exhibited in Figure 3(a). The holes (represented in red) for the bolt placement were selected as displacement restraints and the gripping faces were chosen as the load application surfaces (represented in green). The objective was set to minimize structural compliance, corresponding to an increase in component strength, and the volume fraction to keep was set at 37%. Figure 3(b) shows the results obtained from the TO.



(a) (b)

Figure 3: (a) Boundary conditions selected for the topology optimization and (b) result of the topology optimization.

As one can notice, the obtained claw is ergonomically poor, presenting a rough surface and irregular and non-continuous features. Due to this, surface smoothening was applied to redesign the model and get a good surface finish, as evidenced in Figure 4(a).



(a) (b)

Figure 4: (a) Result of the surface smoothening; (b) Smoothen surface with the updated holes and gripping faces.

As a result of the TO and the smoothening procedure, the holes and the gripping faces were not maintained. Therefore, Boolean operations were used to bring these features back and guarantee their full functionality, as seen in Figure 4(b). This Figure also shows the presence of a stricture point that can lead to stress concentration. Due to this, lattice structures were used to ensure high stiffness in the marked directions. As a last step, lattice structures were also used to add texture to the gripping faces to guarantee a higher gripping power. Finally, the optimized claw was duplicated and rotated to obtain the entire claw.

A single clamp of the original gripper, represented in Figure 2, was also submitted to static analysis simulation. The clamp weighs around 7 g, exhibiting a minimum safety factor of 15 and a maximum displacement of 0,0050 mm. These results make it possible to understand that the clamp is over-dimensioned for the proposed target of withstanding a load of 20 N, which gives a fair margin for the topology optimization.

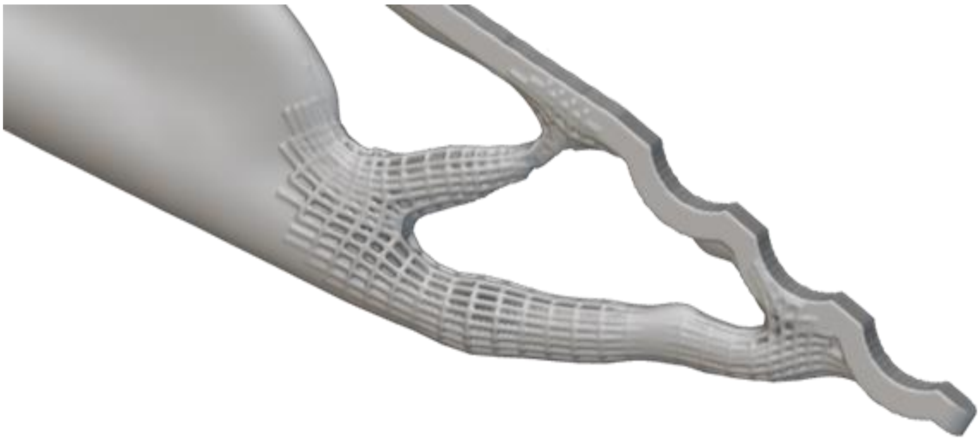
Figure 5(a) and (b) exhibit the result of the topological optimization of one claw and the assembled gripper, respectively. In contrast, Figures 5(c) and (d) allow a better view of the application of the lattice structures for higher rib stiffness and better gripping power. The final clamp resulted in a weight of 4 g, corresponding to a reduction of 43%, and was subsequently submitted to static stress analysis. Figure 6(a), (b), (c), and (d) shows the obtained results for the static analysis test of the optimized clamp, exhibiting data for the safety factor, displacement, strain, and stress, respectively.

The safety factor of three (3) is crucial due to material uncertainties, variable loading conditions, and model limitations, extending the component's resilience over its service life and guarding against wear, fatigue, and degradation. As observed, after a 43% weight reduction, the safety factor was kept above three (3), ensuring a safety margin against potential design flaws. Besides this, the maximum induced displacement is 0,0067 mm, corresponding to about 0,22% of the maximum width. The maximum induced strain is low and applied on the clamp's stricture point.

Lastly, the maximum induced stress was also studied, as it is one of the most important properties resulting from the simulation. This property helps predict whether the component is permanently deformed after it has been submitted to the mentioned loads. Since the yield strength of 316L stainless steel is 250 MPa, and the maximum stress induced (Von Mises) on the clamp is close to 80 MPa, it is possible to infer that the displacement caused in the clamp is not permanent.

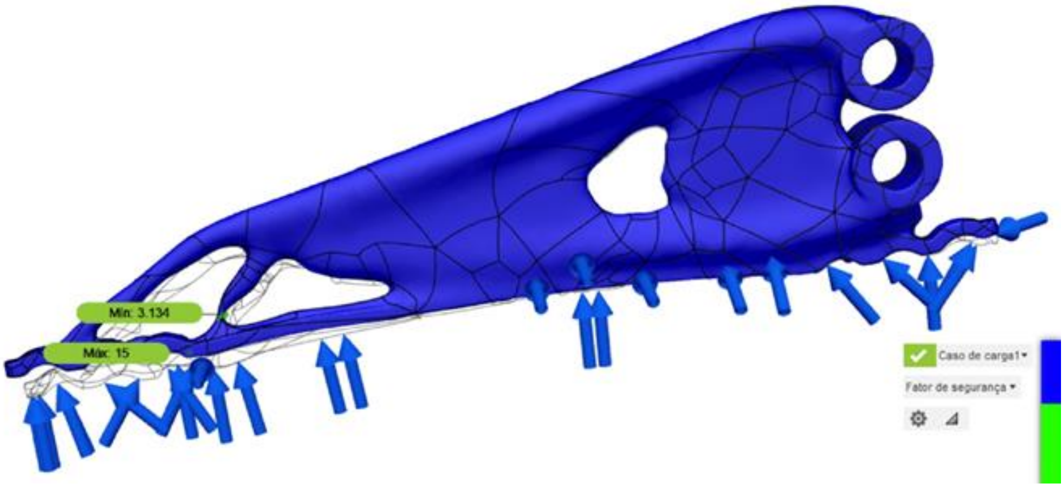
(a)

(b)

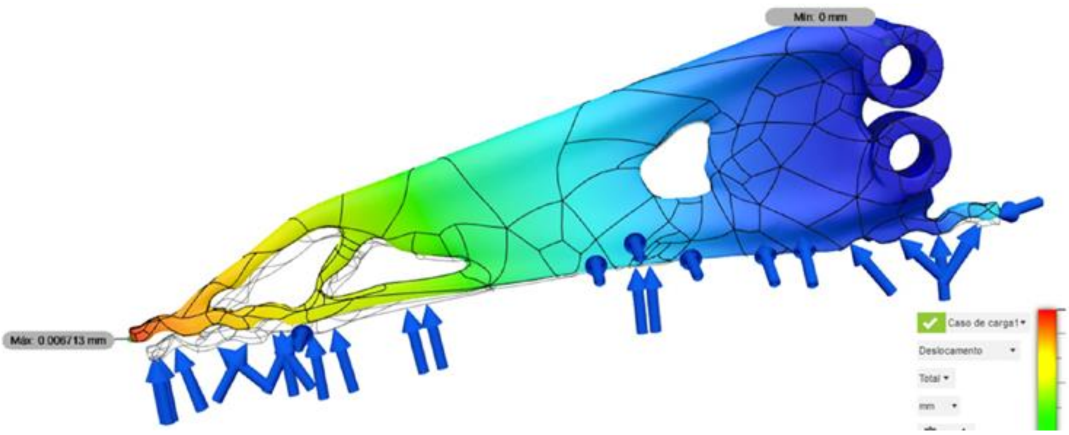


(c)

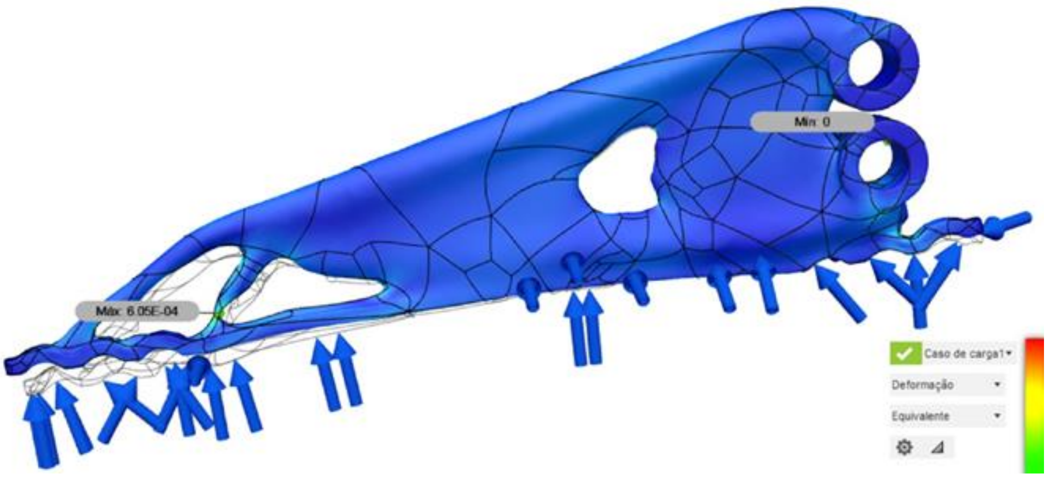
Figure 5: Results of the (a) optimized claw, (b) assembled gripper, (c) lattice structures applied in the ribs and gripping faces.



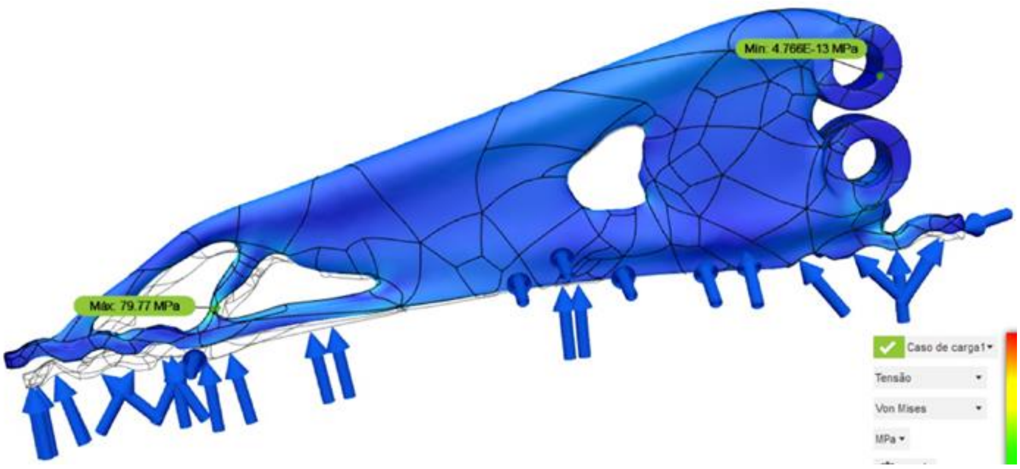
(a)



(b)



(c)



(d)

Figure 6: Results of static test held in Fusion360 for the (a) safety factor, (b) displacement, (c) strain, and (d) stress.

4. Conclusions

This project allowed the first practical contact with the topology optimization process and its variables. After already having close contact with Fusion360, the nTopology software was first tried for optimization purposes, leading to learning, and further understanding of some features of this software.

The static analysis simulation ran on Fusion360 allowed to verify that the original clamp was over-dimensioned for the intended purpose of withstanding a load of 20 N. The topology optimization resulted in a weight reduction of 43% while maintaining a safety factor above 3. Through analysis of the maximum induced stress, it is possible to infer that the deformation caused in the clamp is not permanent.

Simulation and subsequent changes in the design of all four clamps could be carried out for future work to ensure readiness for possible manufacturing. Eventually, the topologic optimization and consequent simulation of a robot gripper more similar and closer to the human hand could occur.

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