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TOPOLOGY OPTIMIZATION FOR MASS REDUCTION OF A STRUCTURAL COMPONENT IN A SURGICAL ROBOTIC ARM

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ABSTRACT

This paper presents a case study on the topology optimization of a structural component in a surgical robotic arm, aiming to reduce mass while maintaining mechanical performance. The component, made of aluminium alloy Al7075-T6, was subjected to finite element analysis and topology optimization using Altair OptiStruct. The objective of the study was to minimize mass under the imposed constraints of maximum displacement (≤ 0.2 mm) and von Mises stress (≤ 250 MPa). The stress limit was selected as 50% of the alloy's yield strength (≈ 503 MPa), to ensure an additional safety margin. Finite element analysis (FEA) was employed to evaluate and validate the optimized geometry. The initial design exhibited a displacement of 0.21 mm and a maximum stress of 240 MPa, which corresponds to a safety factor of 1.04. After optimization, the final design achieved a displacement of 0.18 mm and a maximum stress of 227 MPa, which results in a safety factor of 1.3. These results demonstrate that the adopted topology optimization strategy can effectively reduce structural mass (≈34%) while maintaining compliance with displacement and stress constraints, ensuring reliability for robotic applications.

KEYWORDS: topology optimization; surgical robot; Altair OptiStruct; structural analysis; Al7075-T6; robotic arm component

1. Introduction

Minimally invasive surgery (MIS) has led to a significant demand for lightweight, high-precision robotic systems with excellent dynamic response and structural integrity. In such systems, each component must be optimized for mass efficiency without compromising stiffness or strength [1-2]. Topology optimization (TO) has become a well-established strategy for designing lightweight components, with numerous studies applying it successfully in robotic systems, including manipulators, grippers, and arms [3-5].

The use of topology optimization has expanded with the integration of Computer-Aided Design (CAD) and Finite Element Analysis (FEA) tools, such as HyperMesh and Altair OptiStruct [6-7]. Recent comparative analyses of TO platforms emphasize the importance of solver capabilities, stress-based constraints, and integration with additive manufacturing (AM) workflows [2, 8]. Moreover, lattice-based design methods tailored for AM have shown promising results, enabling further weight reduction through geometric complexity that is not achievable with traditional manufacturing [1, 9-10].

The structural efficiency of robotic components can also be enhanced by combining TO with multi-material optimization [11-12], and by incorporating fabrication constraints like symmetry, minimum member size, and extrusion directions, which ensure manufacturability without sacrificing performance [4, 13-14]. Such comparative reviews highlight that fabrication-aware approaches remain essential for bridging theoretical topology optimization and practical engineering applications [13]. Advanced techniques, such as robustness-based and manufacturing-tolerant topology optimization, have been implemented to handle uncertainty in load cases

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and material properties [15-17]. More recent studies have proposed stress-constrained approaches under uncertain load positions [16], generalized frameworks based on first-order second-moment formulations [18], reliability-based methods incorporating additive manufacturing constraints [19], robust continuum optimization schemes [20], and strategies with local stress constraints and variable load directions. These contributions highlight the continuous evolution of TO toward more realistic and application-oriented design strategies. Studies also show that compliant mechanisms and soft robotic structures benefit from TO methods that consider nonlinear deformation and fatigue life [5, 21]. In this context, novel optimization schemes such as level-set methods, topological sensitivity, and fatigue-driven constraints are gaining traction [14, 21]. Material selection is another key factor. Aluminum alloy Al7075-T6 is widely used in robotic and aerospace structures because of its excellent strength-to-weight ratio, good machinability, and corrosion resistance. With a Young's modulus of about 71.7 GPa, yield strength near 503 MPa, and density of 2,810 kg/m^3, this alloy provides high mechanical performance for lightweight components. It is particularly effective for internal, non-biological-contact parts of medical devices, where biocompatibility is not a primary requirement but stiffness and strength remain essential [22-23, 25].

This paper presents a complete design and optimization workflow for a surgical robotic component, starting from CAD modeling, followed by meshing and structural simulation in HyperMesh, and final-stage topology optimization in Altair OptiStruct. The objective is to achieve maximum mass reduction while ensuring that key mechanical constraints - such as displacement and von Mises stress - remain within safety limits. The approach aligns with recent trends in robotic engineering and contributes to more efficient, precise, and manufacturable designs.

2. Experimental Procedure

The objective of the research was to optimize the structural design of a robotic arm component used in minimally invasive surgery. The experimental procedure included CAD modeling, meshing, topology optimization, and finite element analysis (FEA) validation.

The initial geometry of the robotic arm component was created as a simplified, hollow rectangular structure made of Al7075-T6 aluminium alloy. With overall dimensions of 200 mm in length, 50 mm in width, and 30 mm in height, and a wall thickness of 4 mm, the model represented a typical load-bearing element used in surgical robotic systems. The material selected for the design was Al7075-T6, chosen for its excellent strength-to-weight ratio, high stiffness, and suitability for lightweight structural applications. Its mechanical properties include a Young's modulus of 71.7 GPa, yield strength of about 503 MPa, and density of 2,810 kg/m^3. In addition, this alloy offers good machinability and corrosion resistance, which explains its widespread use in aerospace and robotic components where high mechanical performance is required without biocompatibility constraints.

The CAD model was transferred to Altair HyperMesh for mesh generation and the application of boundary conditions. A first-order tetrahedral mesh with an average element size of 2 mm was created to ensure adequate resolution for structural analysis. To replicate real operational conditions, the component was fully fixed at one end, while a concentrated load of 50 N was applied to the opposite extremity. This simulation setup reflected the mechanical stresses typically encountered by the robotic arm during surgical procedures.

Fig. 1. *Initial 3D CAD model of the robotic component*

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***Fig. 2.** Boundary conditions and applied load on the model*

3. Results and Discussions

After 30 iterations, the topology optimization process produced a geometry with substantial material redistribution. The initial model exhibited a maximum displacement of 0.21 mm and a maximum stress of 240 MPa, values close to the imposed thresholds, which corresponded to a safety factor of 1.04. After optimization, the final design achieved a maximum displacement of 0.18 mm and a maximum stress of 227 MPa, which increased the safety factor to 1.3. The final optimized model achieved a 34% reduction in mass, while fully meeting all mechanical performance criteria. The initial output from the optimization featured irregular surfaces and sharp transitions, which could hinder manufacturability. To address this, the geometry was reimported into a CAD environment and refined using surface smoothing techniques. The final post-processed model preserved the essential structural features of the optimized design while significantly enhancing surface quality, making it suitable for additive manufacturing and practical implementation.

Figure 3 shows the optimized structure, emphasizing its efficient internal layout that ensures stiffness with minimal material use. Figure 4 provides a top-down view, highlighting the non-intuitive load paths and material patterns that emerged through the optimization, specifically adapted to the applied mechanical constraints.

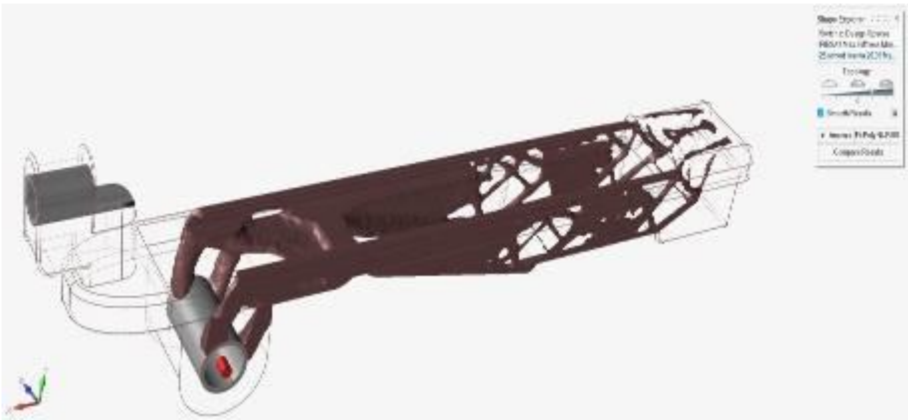

***Fig. 3.** Topologically optimized 3D model*

***Fig. 4.** Top view of the optimized structure showing material distribution*

The maximum displacement recorded was 0.18 mm, and the peak von Mises stress reached 227 MPa, remaining well below the 250 MPa allowable limit.

In a related study, Batista *et al.* [1] reported a 31% mass reduction in a robotic arm component using lattice-based optimization techniques specifically tailored for additive manufacturing. By contrast, the present study achieves a slightly higher reduction using a classical topology optimization approach, without relying on predefined lattice structures. These findings underscore the potential of conventional TO algorithms to deliver high-efficiency structural designs, even before incorporating AM-specific enhancements. Table 1 summarizes the improvements obtained through topology optimization compared to the initial design.

Table 1. *Comparison of mechanical performance before and after topology optimization*

Design Stage	Mass Reduction	Max Displacement (mm)	Max Von Mises Stress (MPa)	Safety Factor
Initial Model	-	0.21	240	1.04
Optimized Model	-34%	0.18	227	1.3

As shown in Figure 5, the side view of the model with superimposed stress distribution confirms that the structural integrity of the component remains intact under the applied loading conditions. Figure 6 illustrates the redistribution of stresses and the continuity of load paths along the optimized ribs. These results collectively demonstrate that the optimized geometry achieves an effective balance between rigidity and lightweight design, validating its suitability for surgical robotic applications.

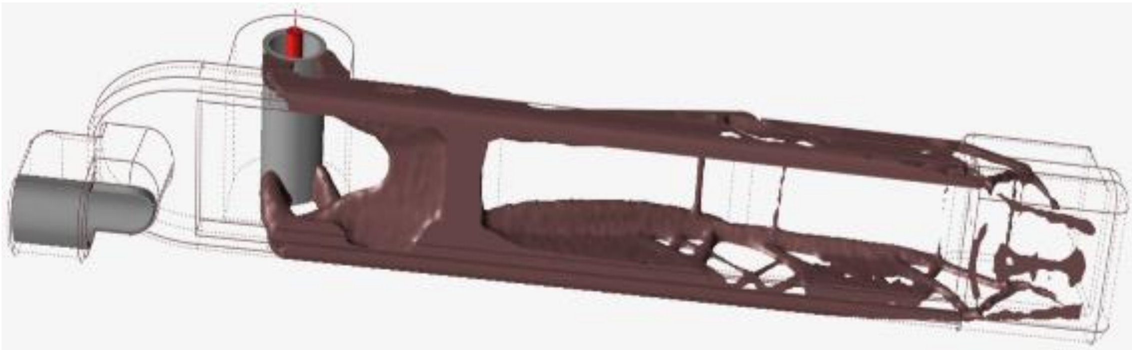

Fig. 5. *The side view of the optimized model showing stress distribution*

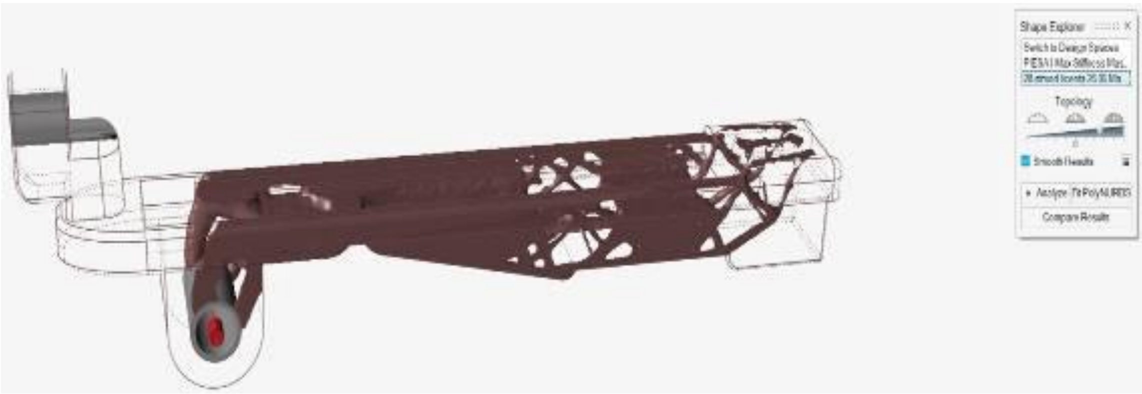

Fig. 6. *The optimized structure from an alternate viewing angle*

The initial output from the topology optimization process featured irregular surfaces and sharp transitions, which could hinder manufacturability and introduce potential stress concentrators. To address this, the geometry was reimported into a CAD environment and refined using surface smoothing techniques. As shown in Figure 7, the final post-processed model preserves the essential structural features of the optimized design while significantly enhancing surface quality, making it suitable for additive manufacturing and practical implementation.

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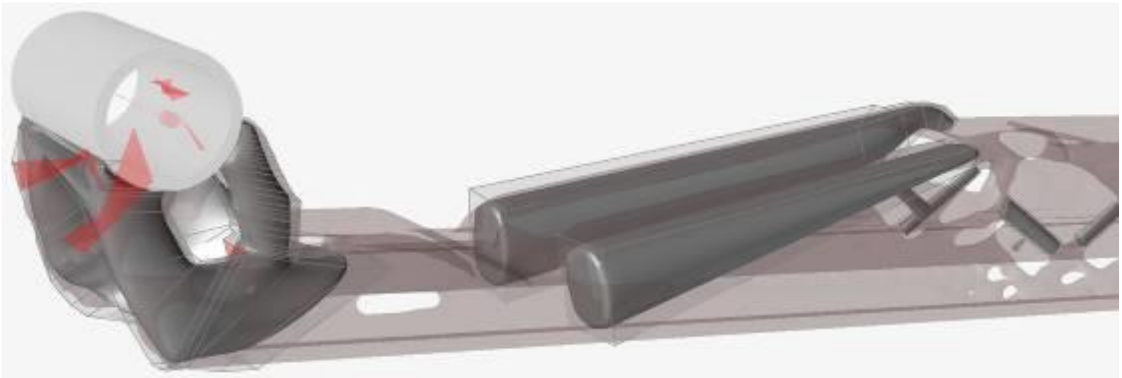

***Fig. 7.** The smoothed and post-processed version of the optimized model*

A final FEM simulation was conducted on the refined model to verify its structural integrity. The results confirmed that all constraints were met, with a safety factor of 1.3, validating the design for surgical robotic applications.

The internal structure of the component resembles trabecular bone, a naturally optimized geometry for stiffness and weight. This result underscores the biomimetic potential of topology optimization in medical device engineering. Moreover, the compatibility of the final geometry with metal 3D printing technologies supports its practical manufacturability, minimizing waste and production time, which are key advantages in customized biomedical device fabrication.

4. Conclusions

This paper demonstrated the effectiveness of applying topology optimization to reduce the mass of a structural component intended for a surgical robotic arm, while ensuring mechanical integrity under realistic operational loads. By employing a CAD-integrated workflow and the Altair OptiStruct solver, a mass reduction of approximately 34% was achieved compared to the original design. The optimization process preserved the required mechanical performance, with a maximum displacement of 0.18 mm and a peak von Mises stress of 227 MPa - both remaining within the defined design limits. The resulting geometry exhibited a non-intuitive, lattice-like internal structure that efficiently redirected stress to critical load-bearing regions, mirroring the efficiency of natural bone structures. To ensure manufacturability, the optimized model was refined through CAD-based post-processing, addressing surface quality and eliminating geometric irregularities. This step rendered the design suitable for fabrication via metal additive manufacturing. The FEM simulations validated that the optimized structure complies with the imposed constraints of maximum displacement (≤ 0.2 mm) and von Mises stress (≤ 250 MPa). The initial configuration exhibited a displacement of 0.21 mm and a maximum stress of 240 MPa, while the final optimized design achieved 0.18 mm displacement and 227 MPa stress, both remaining below the limits. The calculated safety factor was 1.3, indicating adequate structural reliability while achieving mass reduction. These results demonstrate that topology optimization can be effectively applied to robotic arm components, enabling lightweight design without compromising structural integrity. Furthermore, the findings provide a solid numerical foundation for future developments, including experimental validation and the integration of advanced optimization methods into robotic system design.

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