Topology Optimization of End Effector for Staubli TX2-140

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This paper presents a framework for topology optimization applied to the design of the end effector of a Staubli TX2-140 robot. The objective is to minimize the weight of the end effector while maintaining its performance and structural integrity. The optimization process is based on the Finite Element Method (FEM) and adopts a density-based approach with a material interpolation function to capture the optimal distribution of material within the design space. The end effector is modelled as a cantilever beam for ease of computations, conceptual application and related analysis. The preliminary results show that the proposed framework can result in the effective reduction of the weight of the end effector, while preserving its stiffness and performance, and as a result enhancing the overall efficiency of the robot.

I. Introduction

Robots are being increasingly employed in various industries for their high-level of automation, accuracy, and precision. However, their performance relies highly on the design of the end effector, which is the component of the robot that interacts with the environment. A well-designed end effector can greatly improve the efficiency of the robot, whereas a poorly designed one can restrict its capabilities. Topology optimization is a robust tool for designing optimal structures that meet specific performance requirements. It can result in lightweight and high-performance structures by distributing material optimally within a given design space.[1]

The Staubli TX2-140 is a 6-axis, collaborative, easy to program industrial robot that is widely used in various applications, such as manufacturing, assembling and packaging. It has a maximum payload capacity of 5kg, which allows for handling of small to medium-sized parts.*. The robot can be conveniently integrated through assembling associated parts and as a result the design of each part can be discreetly dealt with. The end-effector plays an important role in determining the efficiency of the robot in performing the tasks such as quality testing, packaging and others by operating on a variety of components like automotive parts, electronics, consumer goods, medical devices, etc. Hence, for upgrading these functional characteristics of the robot that enable greater productivity, it is necessary to minimize the weight of the end effector. Fig 1 shows a representation of the Staubli TX2-140 robot.

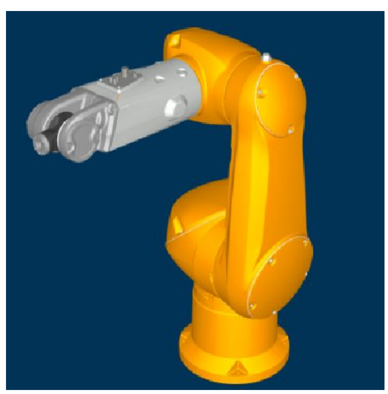

Fig. 1 Prototype of Staubli TX2-10

The paper is organized as follows: Section II presents a brief overview of topology optimization in robotic design and problem formulation. Section III provides the methodology utilized for the topology optimization based on comparison of involved algorithms and methods. Section IV shows some preliminary and expected results of the optimization process. Finally, Section V concludes the paper and proposes future research directions.

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*Staubli Robotics. (2022). Staubli TX2-140. Retrieved from https://www.staubli.com/en/robotics/robot-selector/tx2-series/tx2-140/

II. Topology Optimization in Robotic Design and Problem Formulation

Topology optimization is a computational technique for the design of optimal structures that meet specific performance requirements. This involves distributing material optimally within a given design space to obtain a structure that satisfies predefined objectives and constraints. Topology optimization has been widely used in several fields, such as aerospace, mechanical, and civil engineering. In the context of robot design, it can be employed to design the end effector of a robot to meet certain performance criteria, such as minimizing weight, maximizing stiffness, or reducing stress concentrations. The lightweight structures proposed by this technique can lead to reduced energy consumption, enhanced payload capacity, and greater overall efficiency. In addition, topology optimization is capable of generating innovative and unconventional designs that may not be achievable using traditional design methods, which usually involve enforcing constraints, aesthetics and specifications on the design before optimization.[4]

We formulate the topology optimization problem for the end-effector as follows:

1) The objective function is to maximize the stiffness (or minimize the compliance, which is the reciprocal of the stiffness) of the end effector of the Staubli TX2-140 robot while minimizing its weight. In other words, this stiffness is defined as the ability of the end effector to resist deformation under applied loads. The weight of the end effector is considered as a measure of its material usage and production costs and an estimated value is used from the available information. So, we have:

$$min_{\boldsymbol{x}} \quad \boldsymbol{F}^{\boldsymbol{T}} \boldsymbol{u} \tag{1}$$

where $\boldsymbol{x}$ represents the design variables, $\boldsymbol{F}$ depict the external forces applied to the structure, and $\boldsymbol{u}$ represents the displacement vector of the structure. So, the objective is to minimize the compliance, which is defined as the product of the force vector and the displacement vector. For finite element based approach, this equation is modified as:

$$min\ J = \sum_{n=1} \frac{F_i u_i}{l_i} \tag{2}$$

where n is the number of nodes, F_i is the applied force at node i, u_i is the displacement of node i, and l_i is the length of the element connected to node i

2) The design variables are represented by the material distribution within the end effector. To represent this material distribution, the optimization problem discretizes the end effector into a finite number of cells and assigns a design variable to each cell. This can be formulated as follows:

$$min\ J = \frac{\rho}{\rho_0} V \tag{3}$$

where ρ is the material density, ρ_0 is the reference density, and V is the volume of the structure.

3) The optimization problem needs to satisfy the functional constraints of the end effector. These constraints include maximum stresses, deflections, and natural frequencies. [2] The constraints are formulated as follows: g1(E, W) 0
where g1 is the constraint function that limits the maximum stress, deflection, or natural frequency of the end effector, E is the stiffness and W is the weight of the end effector. Following are some additional constraints which are considered due to the modelling of the end effector of the robot as a cantilever beam:
   - Total volume constraint: It should be less than or equal to a specified value. This is expressed as:

$$\sum_{n=1} V_i <= V_{max} \tag{4}$$

   where n is the number of finite elements in the cantilever beam, V_i is the volume of the i-th finite element, and V_{max} is the maximum allowable volume.
   - Minimum member size constraint: A minimum size constraint is imposed on the members of the end effector to ensure manufacturability and structural integrity. This is expressed as:

$$\rho_i >= \rho_{min} \tag{5}$$

   where ρ_i is the density of the i-th finite element and ρ_{min} is the minimum allowable density.

- Maximum member size constraint: A maximum size constraint is imposed on the members of the end effector to avoid excessive material usage. This is expressed as:

$$\rho_i <= \rho_{max} \tag{6}$$

where ρ_i is the density of the i-th finite element and ρ_{max} is the maximum allowable density.
- Symmetry constraint: The end effector may be required to be symmetric about a plane in certain cases. This can be expressed as:

$$\rho_i = \rho_j \quad if \;\; i, j \;\; \epsilon \quad symmetric\, region \tag{7}$$

where ρ_i and ρ_j are the densities of the i-th and j-th finite elements, respectively, and the symmetric region is defined by the user.

III. Methodology

A. Rationale behind choosing the Density-based topology optimization for this system

There are numerous topology optimization algorithms, each having its unique features, and limitations. Following is a brief overview and comparison of the most common topology optimization algorithms :

1) Density-based topology optimization: It is the most widely used algorithm, which involves discretizing the design domain into a finite element mesh and optimizing the density of material within each element to meet some performance criteria. The density of each element is represented as a continuous variable between 0 and 1, with 0 indicating no material and 1 indicating full material density.
2) Level-set topology optimization: This involves using a level-set function to represent the boundary between material and void in the design domain. A level-set function associated with it is optimized to minimize the compliance of the structure subject to a set of constraints, which are usually the volume fraction, stress, or displacement.
3) Evolutionary topology optimization: This algorithm uses evolutionary algorithms such as genetic algorithms, particle swarm optimization, or differential evolution to develop and evolve candidate designs based on certain fitness criteria, which is typically related to structural performance, that includes stress, stiffness, or natural frequencies.
4) Solid isotropic material with penalization (SIMP) : This involves using a penalty function to penalize intermediate densities of material and create designs that are either solid or void. The penalty function is used to gauge the smoothness of the design and avoids intermediate densities of material from arising.
5) Topology optimization with design-dependent loading: This algorithm revolves around optimizing the topology of a structure subjected to loads which depend on the current state of the structure. This can be used to design adaptive or morphing structures that can change shape or topology in response to external loads.

We have chosen to utilize the density-based approach for the mentioned robotic system.for the following reasons:

- It shows a highly flexible approach for a wide range of applications and performance criteria, including structural stiffness, compliance, and weight optimization.
- It can be implemented using simple and efficient algorithms, such as the Solid Isotropic Material with Penalization (SIMP) method, which lowers the computational cost compared to other methods.
- It is relatively easy to implement, since it requires defining only the density field, and the application of standard finite element methods get the structural response.
- It allows for a high degree of design freedom, since it can generate complex and organic geometries that are difficult to design manually.[7]
- Lastly, it enables us to generate physically realizable designs by imposing constraints on the minimum and maximum density values, such that the resulting designs do not violate manufacturing or material constraints.

B. Rationale behind choosing the Method of Moving Asymptotes

Subsequently, the Method of Moving Asymptotes (MMA) is implemented, which is a popular optimization algorithm used for structural optimization problems. It is a gradient-based optimization method which incorporates a series of asymptotes to approximate the objective function and constraint functions, and update the design variables iteratively. Following are its advantages, for which it is being considered for use in our case:

- Efficient and robust for solving a wide range of optimization problems, particularly effective for problems with a huge number of design variables and constraints.
- Handles nonlinear constraints such as maximum and minimum density values, that are commonly encountered in topology optimization problems.
- Deals with large-scale problems having many design variables and constraints, that makes it well-suited for complex engineering problems.[5]
- Produces smooth and continuous designs using a smoothing parameter, which is important in topology optimization problems to minimize the checkerboard pattern.[6]
- Handles multiple objectives by combining them into a single objective function with different weights, which can be useful in multi-objective optimization problems.[3]

C. Approach used for solving the system

Following is a brief overview of the implementation using these methods to perform topology optimization process:

1) Defining the design domain and discretizing it into finite elements.
2) Assigning an initial density value to each element in the design domain.
3) Declaring the objective function based on the compliance and weight of the end effector. Subsequently, defining the constraints, such as the maximum and minimum density values and the displacement constraints.
4) Employing the method of moving asymptotes to smoothen the density field and reduce the checkerboard pattern. This involved defining a set of smoothing parameters and updating the density field iteratively until convergence.
5) Extracting the optimized density field once the optimization process is complete and generating the final design by thresholding the density values to obtain a binary topology.
6) Performing a finite element analysis on the final design to verify its performance and evaluating any extra criteria such as stress and strain, if required.
7) Iterating the above steps until the desired level of performance is attained.

IV. Preliminary results

The methodology presented above was translated into a Python code that sets up the optimization problem using OpenMDAO and PyOptSparse. It defines the objective function, constraints, and design variables, and sets up MMA optimizer with the method of moving asymptotes. Finally, it runs the optimizer and prints the results. As of now, the optimizer part of the code needs modification to suitably operate on the model and as a result, the results could not be shown.

It is expected that the model would generate an optimized design and the same can be verified by using applications developed to perform topology optimization of 2D structures.

V. Conclusion

In this study, a topology optimization framework was generated and applied to optimize the end effector of the Staubli TX2-140 robot. A bi-objective problem was formulated with the objectives of minimizing the weight and maximizing the stiffness of the end effector. The method of moving asymptotes (MMA) algorithm was employed to perform the optimization, and additional constraints were enforced to ensure the manufacturability of the optimized design. The proposed framework can be extended to optimize other components of the robot, such as the robot arm and base, to further enhance the overall performance of the robotic system. Future work can focus on the experimental validation and subsequent implementation of the optimized design of the end effector. The proposed topology optimization framework can additionally be applied to other industrial robots and applications, acting as a powerful tool for the design and optimization of robotic systems.

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