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A Simulation and Optimization Methodology Based on Reverse Engineering †

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Abstract: Simulation and optimization have become common tasks in engineering practice due to their advantages, namely cost reduction and unlimited testing prior to manufacturing. Over the last few years, personal computers have become powerful enough to run complex simulations. On the other hand, the industry has seen an increase in automation, where repetitive tasks carried out by humans in the past are gradually being replaced by robotic systems. Those robotic systems usually involve a robotic arm, a gripper, and a control system. This article presents a methodology for the simulation and optimization of existing engineering parts, i.e., based on reverse engineering. The models were subjected to static loadings and free vibration (modal) analysis in the finite element method (FEM) software ANSYS Workbench 2021 R2. The adaptive multi-objective optimization algorithm was also applied in ANSYS Workbench 2021 R2. The effectiveness of the proposed methodology was evaluated, and the outcome was that significant improvement could be achieved in terms of both the static and dynamic behavior of the analyzed part.

Keywords: reverse engineering; robotic gripper; finite element method; optimization

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1. Introduction

Deformable item manipulation is a rapidly expanding field of robotics research with applications in home, manufacturing, and recycling [1,2]. Fabric manipulation has prompted the development of a number of end effectors [1–3]. Haptic exploration, alternate grasping movements, and skilled manipulation were all demonstrated in prior research. A majority of end-effectors will be capable of gripping material in general settings due to fabric conformance to the grasp motion. However, under certain circumstances, such as when the cloth appears to be leveled, this first hold becomes more difficult. In the literature, approaches that take into consideration and use environmental restrictions to aid gripping have been presented [3–5]. Various studies have tried grasping this situation using a range of effectors and various gripping movements [2,3]. There are some research works that employ biomimetic grasping, which entails dragging a finger across a surface to create a protrusion in the fabric's body that the effector may grip [5–8]. There has been some numerical work, namely in simulation and optimization of robotic grippers, aiming to predict and/or improve their behavior in real engineering applications [9–12]. Robotic gripper design optimization is crucial for stable grasping. The article [9] analyzes the best design of an under-actuated tendon-driven robotic gripper with two 3-phalange fingers and proposes a geometric design optimization method to achieve steady grab performance. The challenge involves 22 design variables, including phalange lengths, widths, mandrel radii, palm breadth, and route variables for six pulleys. First, the active and contact forces are modeled using the robotic gripper's dimensions. Second, a geometric model of tendon paths is created to reduce resistance. Next, two fitness models use three goal functions and several geometric restrictions. Finally, the genetic algorithm optimizes the models.

The proposed method is validated via experimentation. The method optimizes any underactuated tendon-driven gripper [9]. Robot design and control require structure modeling and optimization. In the work [10], the authors modeled and optimized a robot structure. A closed-loop, single-DOF robot gripper device illustrates this procedure. The authors' goal was to explore the gripper in detail to explain the design process and its relationships. First, a geometric model was created to determine the relationship between the end-effector coordinates and joint coordinates. A kinematic model was found using an equivalent Jacobian matrix, and the dynamic model was found using Lagrange formulation. Based on these models, a static gripper multi-objective optimization problem was formulated. The optimal force extracted by the robot gripper on a grabbed stiff object under geometrical and functional limitations was determined. Non-dominated sorting genetic algorithm version II optimized the gripper design (NSGA-II). The authors examined Pareto-optimal strategies to construct meaningful links between the objective functions and variable values. A design sensitivity analysis computed objective function sensitivity to design variables [10]. In [11], the research used intelligent strategies to optimize a robot gripper's geometry. This problem includes five objective functions, nine constraints, and seven variables. Three cases are presented. Case 1 considers the first two objective functions, case 2 last three, and case 3 all five. Intelligent optimization methods (MOGA, NSGA-II, and MODE) are presented to solve the problem. Two multi-objective performance measures (SSM and RNIs) are used to evaluate Pareto optimum fronts. Two more multi-objective performance measurements, optimizer overhead (OO) and algorithm effort are utilized to find MOGA, NSGA-II, and MODE's computational effort. The Pareto optimum fronts are obtained, and results from different methodologies are compared and analyzed [11]. The aim of the present work is to test a methodology that involves reverse engineering an existing CAD design of a gripper, simulating it, setting it up, and running a design optimization routine. The ultimate goal is to obtain a part with optimized mechanical behavior with the least mass possible to improve motion capabilities. The need to develop and implement this methodology is related to advantages in practical applications, which is the main contribution to the improvement in mechanical behavior, both static and dynamic (modal), associated with mass minimization. The main contribution of this work is the application of an optimization methodology that is effective in optimizing both static and dynamic behavior in one step. Although from a scientific point of view, there was no breakthrough, the study is very useful for the G4FM project because it allows us to conclude that the parameters P1, P2, and P3, as well as the optimization (objectives), are suitable for the goals of the project and can be used in other geometries, i.e., with internal channels, for example.

2. Numerical Procedure

This work used a reverse engineering-based approach. This method allows one to reduce project development times because it is based on existing solutions that are known to be functional. The focus is therefore on improving existing solutions. The work presented followed a methodology which can be applied to reverse engineering problems involving CAD design and simulation, as shown in Figure 1.

The CAD model of a gripper was downloaded from the Web [13] and imported into the Design Modeler of ANSYS Workbench. Simulations were carried out in the FEM software ANSYS Workbench 2022 R1. Both static and modal simulations were carried out. The simulation conditions are shown in Figure 1, mainly loads and DOF constraints. The material properties used in the simulations are those of Silicon Rubber: density = 1240 [kg/m^3], Young's Modulus = 79.3 [MPa], and Poisson = 0.49 [-]. The material properties were taken from [14]. However, for the computation of the bulk modulus to be possible, Poisson's coefficient was lowered from 0.5 to 0.49. The optimization type used was adaptive multi-objective, based on the genetic algorithm. The objective function took into consideration the minimization of mass and linear deflections, as well as the maximization of resonance frequencies of the first 5 vibration modes.

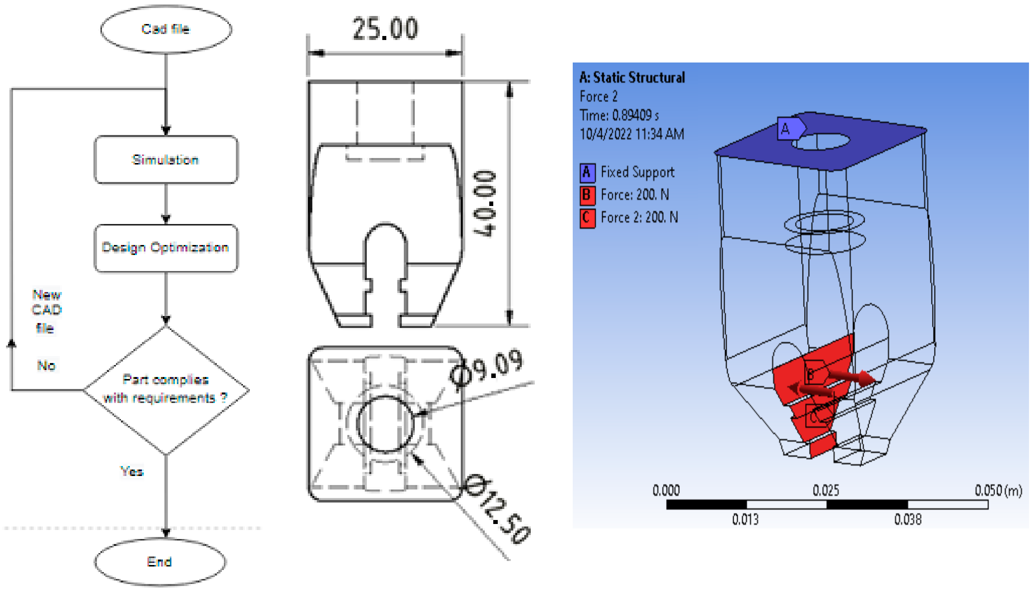

Figure 1. Flowchart of the methodology proposed in this work (**left**), CAD model of the gripper (**middle**), and loads and DOF constraints (**right**).

3. Results and Discussion

3.1. Evaluation/Assessment

The design of the gripper should be optimized to allow for greater mobility when integrated into the robotic arm by reducing the mass. Associated with the decrease in mass, there is usually an increase in stresses and displacements, so, simultaneously, this trend should be countered, minimizing stresses and displacements. The minimization of stresses allows for a wider range of suitable materials, and the minimization of displacements allows for greater safety in terms of not reaching the plastic domain, which makes it impossible to use the gripper. The evaluation of the applied methodology is carried out by comparing the relevant criteria, stresses, displacements, and mass of the optimized solution with the initial solution. The evaluation of the effectiveness/usefulness of the approach was quantified via the Expressions (1) and (2) for modal and static analysis, respectively.

$$Imp_{b/\mathrm{var}}[\%] = \frac{x_{ai+1} - x_{ai}}{x_{ai}} \times 100 \quad (1)$$

$$Imp_{a}[\%] = \frac{x_{bi} - x_{bi+1}}{x_{bi}} \times 100 \quad (2)$$

where $\mathrm{x_a}$ represents natural frequencies (in modal analysis) and $\mathrm{x_b}$ represents the linear deflections according to the longitudinal axis in the static analysis, or the linear deflections of the first non-stiff mode in modal analysis (seventh natural mode).

The design optimization was driven by an objective function that has the meaning of minimization of linear deflections in both static and modal analysis. The linear deflections (x axis) were used in static analysis and the linear deflections (x axis) in modal analysis of the mode 7 (first non-stiff mode) were used.

3.2. Optimized Model vs. INITIAL

Figures 2 and 3 compare the results of the initial model with those of the optimized model, whose parameter values are shown in Table 1. Figure 2 shows the Linear deflection (x axis) for the optimized model (left) and for the initial model (right). Figure 3 shows the Huber–Mises strength for the optimized model (left) and for the initial model (right).

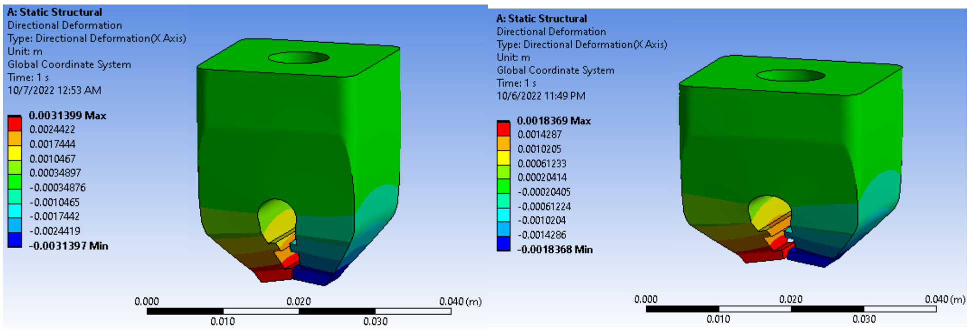

Figure 2. Results from static analysis: linear deflection, x axis, initial (**left**) and final (**right**).

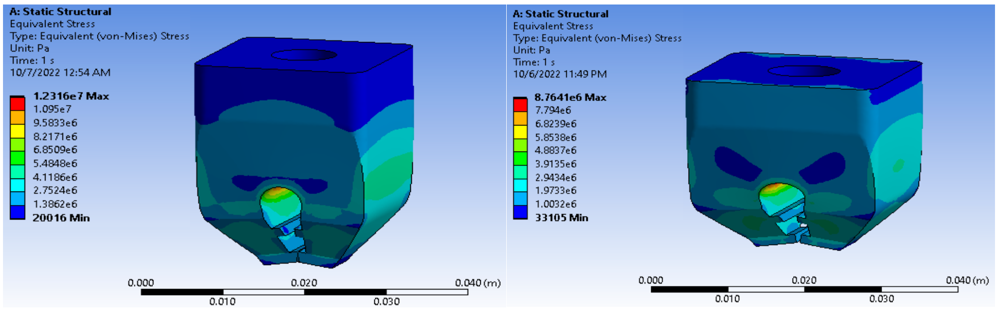

Figure 3. Results from static analysis: Huber-Mises strength, initial (**left**) and final (**right**).

Table 1. Comparison between the initial and final parameters.

	Initial [mm]	Optimized [mm]	Variation [%]
Parameter ID 1	25	28.6000	14.40
Parameter ID 2	40	42.8200	7.05
Parameter ID 3	25	22.0519	−11.79

The initial and final value of the parameters is shown in Table 1, along with the value of the objective function. The variation, shown in Table 2, was obtained via the application of Equation (1).

Table 2. Results comparison between the initial and optimized model.

	Initial	Final	Imp [%]
δy [mm]	3.140	1.837	41.50
σ_{HM} [MPa]	12.316	8.764	28.84
mass	12.96	13.241	−2.17

3.3. Simulation

Figure 4 shows the frequency shift due to optimization for all studied modes.

In Figure 5, it is noticeable that the frequency shift is positive for most modes, with improvements ranging from slightly below 5 up to slightly above 15%. Mode 4 is the one that shows a shift in the opposite direction (negative shift), comparing the optimized model with the initial one. Table 2 shows the comparison between the initial and optimized models in static analysis.

From Table 2, it can be concluded that, with an increase in mass of 2.17%, the deflections decreased by 41.5%, and the Huber–Mises equivalent strength decreased by 28.84%. These results prove the feasibility of the applied objective function, as well as the defined geometric parameters, P1, P2, and P3.

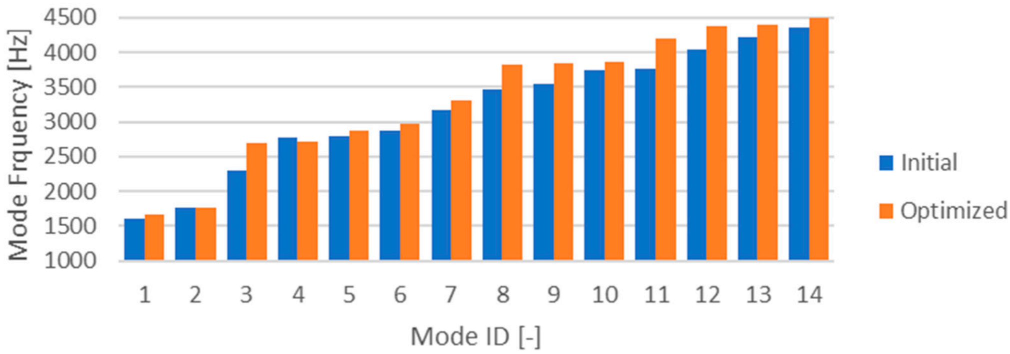

Figure 4. Frequency shift due to optimization for 14 natural modes.

Figure 5 shows the improvement in frequencies (shift), given by the application of Equation (1) to the data of Figure 4.

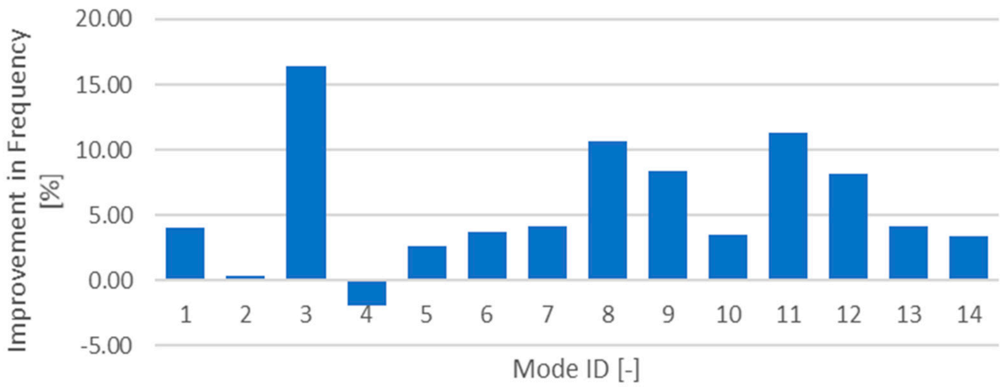

Figure 5. Improvement in frequencies resulting from optimization for 14 natural modes.

4. Conclusions and Future Work

The objective function, defined as the minimization of mass and linear deflections and the maximization of minimum fatigue life, was effective in improving the mechanical behavior of the gripper under study. The optimization methodology, applied to the FEM models of the grippers, was effective in improving the mechanical behavior of the part. The methodology applied in design optimization is useful for improving the static and dynamic behavior of the parts in a single step. In the future, the methodology used could be applied to other grippers, and the optimized gripper could be manufactured and experimentally tested. The aim of this study was to assess whether parameters P1, P2, and P3, as well as optimization conditions (objectives), are appropriate for project targets and can be used in other geometries, i.e., with internal channels, for example. The objective of achieving adequate conditions for significant improvement was attained. In the future, the geometry can be replaced with any other one, applying the same conditions. The improvement is also expected to be significant, although not exactly the same.

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