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A Simulation and Optimization Methodology Based in Reverse Engineering †

Hugo Miguel Silva[1,2]

[1] CiTin—Centro de Interface Tecnológico Industrial, Passos, Largo da Feira 5, 4970-786 Guilhadeses, Arcos de Valdevez, Portugal; hugo.silva@hmsilva.science

[2] proMetheus, Instituto Politécnico de Viana do Castelo, Rua Escola Industrial e Comercial de Nun'Álvares, n.º 34, 4900-347, Viana do Castelo

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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 years, personal computers have become powerful enough to run complex simulations. On the other hand, industry has seen an increase in automation, where repetitive tasks done 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 (AMO) algorithm was applied, also in ANSYS Workbench 2021 R2. The effectiveness of the proposed methodology was evaluated, and the outcome was that significant improvement can be achieved in terms of both 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 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 objective functions and several geometric restrictions. Finally, the genetic algorithm optimizes the models. The proposed method is validated through experimentation. The method optimizes any under-actuated tendon-driven gripper [9]. Robot design and control require structure modeling and optimization. In the work [10], the authors modelled and optimized a robot structure by means of a closed-loop, single-DOF robot gripper device. The authors' goal is to explore the gripper in detail, to explain the design process and its relationships. First, a geometric model is created to determine the relationship between the end-effector coordinates and joint coordinates. A kinematic model is found, using an equivalent Jacobian matrix, and the dynamic model is found using Lagrange formulation. Based on these models, a static gripper multi-objective optimization problem is formulated. The optimal force extracted by the robot gripper on a grabbed stiff object under geometrical and functional limitations is determined. Non-dominated sorting genetic algorithm version II optimizes the gripper design (NSGA-II). The authors examine Pareto-optimal strategies to construct meaningful links between the objective functions and variable values. Design sensitivity analysis computes objective function sensitivity to design variables [10]. In [11], the research uses 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 objective functions, and case 3 all five objective functions. 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 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 and subject the gripper to a design optimization routine. The ultimate goal is to get 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 engineering applications, being the main objective of the work contribution the improvement of 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 to optimize both static and dynamic behavior. This study allows one to conclude that both the selected design optimization parameters and the optimization objectives are suitable for the goals of the project. The methodology followed in this work can be used in other geometries, with internal channels, for example.

2. Numerical Procedure

This work used a reverse engineering-based approach. This method allows you to reduce project development times because it is based on existing solutions that are known to be functional. The focus of this work is therefore placed on improving existing solutions. The CAD model of a gripper was downloaded from the web [13] and imported into Design Modeler of ANSYS Workbench. Simulations were carried out in the FEM software ANSYS Workbench 2022 R1

The work presented followed the methodology, as shown in fig. 1 (left).

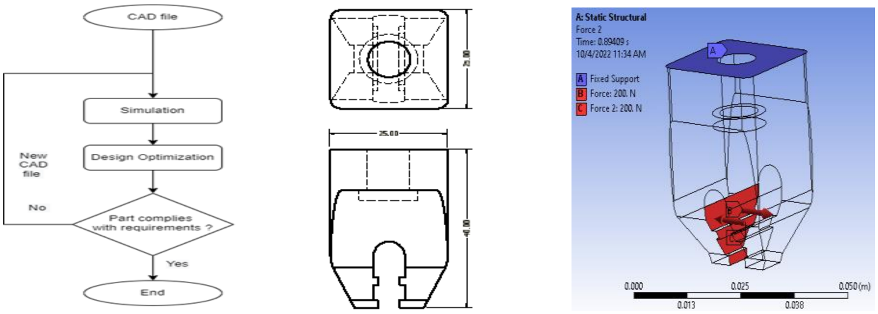

Fig. 1. Flowchart of the methodology proposed in this work (**left**), CAD model of the gripper (**middle**) and Loads and DOF constraints (**right**).

Both static and modal simulations were carried out. The simulation conditions are shown in fig. 1 (right), mainly loads and DOF constraints. The material properties used in the simulations are those of Silicon Rubber: Density = 1240 [kg/m^3] and 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, the Poisson's coefficient was lowered from 0.5 to 0.49. The optimization type used was Adaptive Multi-objective (AMO), based on 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.

3. Results and Discussion

3.1. Evaluation/Assessment

The design of the gripper should be optimized to allow for greater mobility in the future, 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, by also minimizing the stresses and displacements. The minimization of the stresses allows a wider range of suitable materials, and the minimization of displacements allows greater safety in terms of not reaching the plastic domain, with which make it impossible to use the gripper. The evaluation of the applied methodology is done by comparing the relevant criteria, namely stresses, displacements and mass of the optimized solution with the initial solution. The evaluation of the effectiveness/usefulness of the approach was quantified by expressions (1) and (2), for modal and static analysis respectively.

$$\mathrm{Imp_b\ /Variation\ [\%]} = \frac{x_{ai+1} - x_{ai}}{x_{ai}} * 100 \tag{1}$$

$$\mathrm{Imp_a\ [\%]} = \frac{x_{bi} - x_{bi+1}}{x_{bi}} * 100 \tag{2}$$

where:

x_a represents natural frequencies (in modal analysis), x_b represents either Huber-Mises Stress, linear deflections according to the longitudinal axis in static analysis or the linear deflections of the first non-stiff mode in modal analysis (the 7th natural mode, in this case). The design optimization was driven by an objective function that can be represented by Eq. 3:

$$Obj = \frac{\delta x}{\delta x_i} + \frac{\sigma_{HM}}{\sigma_{HM\,i}} + \frac{m}{m_i} \tag{3}$$

where:

σ_{HM} is the Huber-Mises Stress; δx is the linear deflections (x axis) in static analysis; the letter i refers to the initial model. In modal analysis δx is the linear deflections (x axis) in modal analysis, of the mode 7 (first non-stiff mode).

3.2. Static analysis

Figs. 2 and 3 compare the results of the initial model with those of the optimized model, whose parameter values are shown in table 1. Fig. 2 shows the linear deflection (x axis), for the optimized model (left) and for the initial model (right).

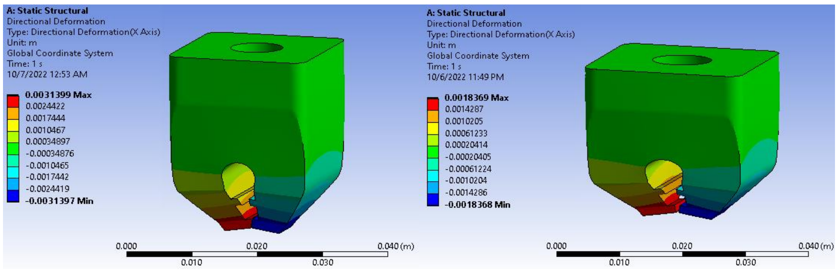

Fig. 2. Results from static analysis: linear deflection, x axis, initial (**left**) and final (**right**).

Fig. 3 shows the Huber-Mises strength for the optimized model (left) and for the initial model (right):

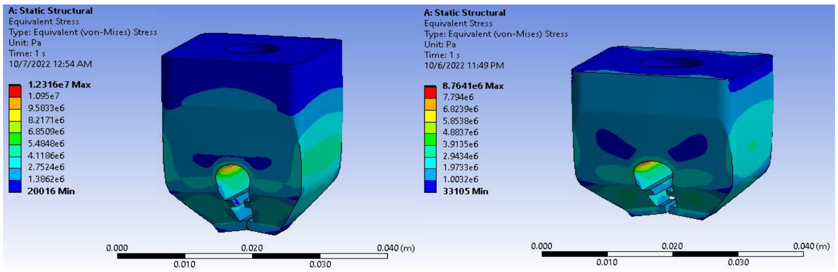

Fig. 3. Results from static analysis: Huber-Mises strength, initial (**left**) and final (**right**).

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 by the application of eq. (1).

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

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

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 41.5% and the Huber-Mises equivalent strength decreased 28.84%. These results prove the feasibility of the applied objective function, as well as the defined geometric parameters, P1, P2 and P3.

3.3. Modal analysis

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

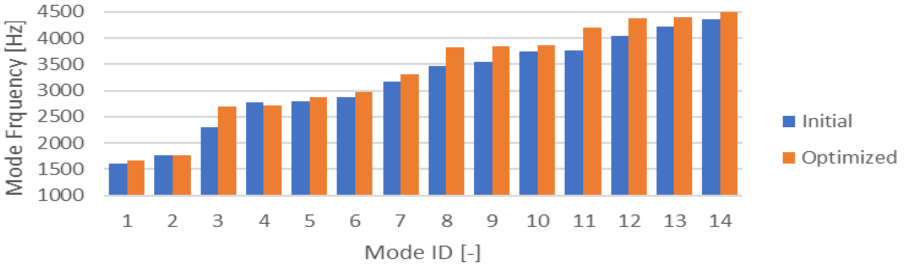

Fig. 4. Frequency shift due to optimization, for 14 natural modes.

Fig. 5 shows the improvement in frequencies (shift), given by the application of eq. (1) to the data of fig. 4.

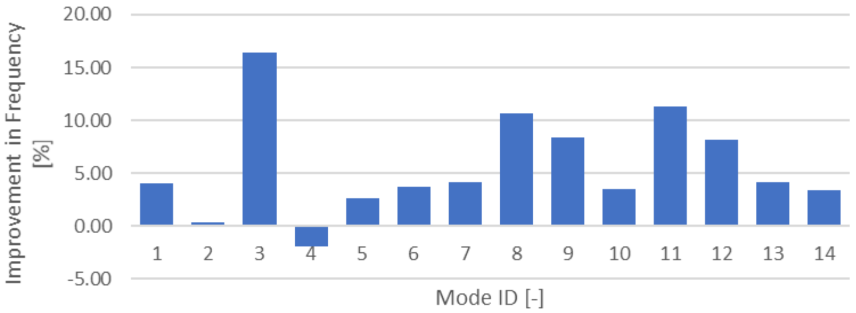

Fig. 5. Improvement in frequencies, resultant from optimization, for 14 natural modes.

In fig. 5, it is noticeable that the frequency shift is positive for most modes, with improvements ranging from slightly below 5 up to slightly above than 15%. Mode 4 is the one that shows shift in the opposite direction (negative shift), comparing the optimized model with the initial one.

4. Conclusions and Future Work

The following conclusions can be inferred from this work:

-The objective function, defined as the minimization of mass, linear deflections and Huber-Mises strength, was effective in improving the mechanical behavior of the gripper under study.

-The optimization conditions were suitable for the design optimization of the gripper

-The mechanical behaviour of the studied gripper can be substantially improved by mean of design optimization.

-In the future, the methodology followed could be applied to other grippers and the optimized gripper could be manufactured and experimentally tested.

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