Implementation of Surface Response Optimization in the Design of Adaptive Lightweight Gripper

Mohammad Al Mashagbeh [1,*], Saleh K. Elayyan [2], and Migdad Tamimi [3]

[1] The Department of Mechatronics Engineering, The University of Jordan, Amman, Jordan
[2] The Department of Mechanical Engineering, The University of Jordan, Amman, Jordan
[3] The Department of Computer Engineering, The University of Jordan, Amman, Jordan
Email: m.mashagbeh@ju.edu.jo (M.A.M.); sal8210064@ju.edu.jo (S.K.E.); mqd8230581@ju.edu.jo (M.T.)
*Corresponding author

***Abstract*—Robotic grippers play a vital role in enabling robots to efficiently manipulate objects. This study primarily focuses on the design and optimization of an adaptive gripper using response surface optimization techniques. A new design based on response surface optimization utilizing ANSYS software is suggested in place of the original design based on complaint mechanism topology optimization. The study aims to develop a lightweight gripper with the best flexibility for gripping items. When determining the optimal set of input parameters, the response surface optimization technique is used to consider objectives such as maximizing deformation and decreasing mass. The considerable impact of specific factors on deformation, stress, and mass is highlighted through sensitivity analysis. The relationship between mass and deformation is depicted in the trade-off curve, demonstrating a significant exponential decrease in mass as deformation increases. Response surface analysis guides the selection of potential locations, leading to the identification of the optimal design parameters. Surface response optimization indicates that the adaptive finger can achieve a substantial 37 mm deformation, highlighting its remarkable flexibility relative to its weight and stress tolerance. The proposed design has a final mass of 10 grams, which is relatively lightweight in comparison to other designs documented in the literature.**

***Keywords*—gripper, design, optimization, simulation**

I. Introduction

Robotic grippers are devices that allow robots to pick up and manipulate objects. They are an essential part of many mechanical systems, and their performance can significantly impact a robot's overall productivity and efficiency [1]. Recent literature features an array of studies delving into diverse gripper designs and optimization methodologies. These investigations underscore the enhancements in gripper strength, repeatability, and speed when compared to their older designs. They also emphasize how technical developments have aided in the creation of grippers that can hold a variety of things [2].

Grippers have many different types depending on the application. Pneumatic grippers are among the most used in the small and medium industries [3]. These kinds of grippers are used for on-off control regardless of the force control [4]. Actuation strategies for soft robotic grippers are also examined. Fluid Elastomer Actuators (FELA) are one of the most established and widely used methods for soft robotic grippers. Lightweight, high power-to-weight ratio, big stroke and force output, simplicity of manufacture, resilience, and low-cost materials are just a few benefits of FELA-based soft grippers [5–8]. A soft gripper system utilizing Fluidic Prestressed Composite (FPC) fingers develops an analytical model to examine grasping capabilities, considering factors like pre-strain, integration angle, and finger overlap. The model's predictions align with experimental results, offering insights into theoretical analysis for soft robotic grippers [9].

A bio-inspired conformable helical soft fabric gripper introduced with variable stiffness and touch sensing in the realm of soft robotic grippers. The gripper is thin, lightweight, and scalable, and it is made using a computerized approach from apparel engineering. A small hydraulic source controls the gripper, which can grab items of various sizes and weights. The research shows the value of employing conformable matrix materials in soft robotic grippers and emphasizes how well FEA-based grippers can hold items of varied sizes [10]. A novel soft actuator concept for enhancing the capabilities of soft grippers proposed by employing a dual-chamber structure filled with engineered particles, this actuator achieves large-scale deformation and variable stiffness, offering the potential for versatile applications in soft grippers. Numerical modeling confirms its effectiveness, demonstrating substantial bending and stiffness improvements compared to traditional actuators [11].

The medical field also has several applications for robotic and manual grippers, one research describes an automated approach for creating customizable surgical

Manuscript received September 24, 2024; revised November 11, 2024; accepted December 26, 2024; published May 9, 2025.

forceps. Although compliant forceps are used for their ease of disinfection, they frequently lack adaptive gripping. Using topology optimization, this technique simplifies the design of task-specific compliant forceps, providing safe manipulation. Experiment results demonstrate its efficacy [12]. A MATLAB-based Finite Element Method (FEM) framework for investigating complicated bio-inspired compliance mechanisms utilized in medical robots was introduced. It tackles non-linear FEM modeling concerns by handling massive displacements, tendon-driven systems, and contact problems. Simulations validate their accuracy, and structural optimization of these systems is also possible [13].

Furthermore, there is a variety of research focused on investigating a diverse range of gripper designs and optimization methodologies in recent literature, demonstrating the dynamic and growing environment of this topic [14–21].

Extensive research efforts have been undertaken in the field of optimizing robotic grippers, embracing a wide range of investigations and developments. One uses Strength Pareto Evolutionary Algorithm 2 (SPEA2) to suggest a multi-objective design optimization strategy. The goal of the study is to optimize the gripper design by considering a variety of factors, such as increasing the grabbing force while reducing weight and energy consumption. The results show how well the suggested method works in locating the best gripper designs that strike a compromise between efficiency and performance [22]. Another research was conducted to address the requirement for a versatile, sensor-free soft robotic gripper that can handle objects that vary in size, shape, and softness. It describes a revolutionary strategy for creating a basic yet adaptive two-finger gripper by combining compliant mechanisms with a linear actuator. Simulation and prototype studies show that it is capable of securely and gently grabbing a wide range of objects, even those that are difficult to grasp, such as soft fruits and irregular forms. This gripper provides an excellent solution without the need for sensors or sophisticated control systems [23].

A novel MATLAB-based 3D topology optimization system was proposed for automating the design of soft robotic grippers capable of grabbing irregularly shaped objects. The framework streamlines the design process by allowing users to specify the design domain and set boundary conditions. To produce 3D-printable soft grippers, it uses 3D topology optimization and post-processing techniques. Experiment results show that they are effective at gripping items of varied forms, revealing prospective uses for soft grippers with variable actuation systems and specialized grasping characteristics [24]. The compliant gripper with parallel gripping motion through topology and dimensional synthesis was introduced. The approach combines topology optimization to generate compliant mechanisms and evolutionary optimal design for various goals. A kinetostatic model is developed for force-displacement analysis, validated through experiments, demonstrating the efficiency and accuracy of the design process [25].

A recent research project aims to call attention to the significance of adaptive grasping in robotic grippers, particularly continuum-structure grippers, which are noted for their flexibility. It offers a new continuum-structure double-finger gripper with an additional spring for adaptive gripping, optimized utilizing a 3-D topology method. In testing, the gripper, which was made utilizing selective laser sintering using polyamide material and controlled by a linear motor, effectively handled various items. Despite its small weight (180 g), the gripper managed an impressive maximum payload of 8.8 kg or roughly 49 times its weight. This study concisely illustrates the viability of optimization-based automated design for robotic grippers [26]. An impressive methodology was proposed for improving the handiness of two-fingered grippers by optimizing finger size, investigating symmetry effects, and examining the workspace. The findings led to the development of an adaptable gripper with adjustable finger bases and locked joints, which improves manipulation without losing efficiency. The gripper functions as a parallel jaw as well as an adaptable gripper [27].

In this paper, a new design of a lightweight gripper is introduced. The design idea comes from the need for soft, adaptive grippers that can grasp things in different sizes without mechanisms and many parts. This paper presents the design formulated through response surface optimization using ANSYS software. The design was conducted by investigating a set of parameters to reach the optimum value for each parameter to improve the bending performance of the gripper. The goal of the optimization procedures is to maximize the deformation and minimize the mass. The design values are updated from the optimization analysis to obtain the desired total deformation and stress values. Finally, a validation approach is used to generate a 3-D-printable model based on the optimized parameters.

The fundamental design criteria for the proposed adaptive lightweight gripper are to achieve maximal deformation for increased flexibility while limiting bulk to maintain a lightweight structure. These specifications are driven by the gripper's intended usage in industrial automation, where adaptability to items of diverse sizes and forms is crucial. Furthermore, structural stability under stress and cost-effectiveness in production are important issues. These criteria were converted into precise optimization objectives, such as increasing deformation (with a target range of up to 40 mm) and reducing mass (resulting in a final weight of 10 g). Additional factors, such as ease of manufacture utilizing readily available 3D printing materials like PLA, were incorporated into the design process.

II. Overview of Optimization Design Methods

3-D Topology Optimization-Based Design Methods are effective for producing optimal structural designs in various engineering applications. These approaches use mathematical algorithms to distribute material repeatedly within a defined design domain, attempting to reduce specific performance requirements while meeting certain limitations. Topology optimization can provide optimal designs with greater structural efficiency, decreased weight, and higher performance by methodically eliminating unneeded material and redistributing it where it is most required. These approaches have been used effectively in various sectors, including aerospace, automotive, and civil engineering, to create lightweight, high-performance structures. Density-based approaches, such as Solid Isotropic Material with Penalization (SIMP), and level-set-based methods, such as the Extended Finite Element Method (XFEM) are notable in this field. These methods are effective [28].

Response surface optimization is a technique used to find the best combination of input parameters for a given output. It can be used in a variety of engineering applications, such as design optimization, process optimization, and product development. ANSYS provides several tools that can be used for response surface optimization. These tools include Response Surface Methodology (RSM), Design of Experiments (DOE), and Optimization. RSM is a statistical technique that can be used to develop a mathematical model of the relationship between the input parameters and the output. DOE is a technique that can be used to select a set of input parameters to be used in the RSM model. Optimization is a technique that can be used to find the best combination of input parameters for the given output [28–32]. To use ANSYS for response surface optimization, you will need to define the input parameters and the output, select a DOE method, generate a DOE plan, run the simulations, fit the RSM model to the simulation data, and finally use the RSM model to find the best combination of input parameters.

III. Design Methodology of the Proposed Adaptive Finger

A. *Response Surface Optimization*

This study's theoretical foundation is based on optimization and structural analysis methodologies, specifically Response Surface Optimization (RSM). RSM is a well-established statistical and mathematical tool for modeling and analyzing problems in which numerous variables influence the interest response. Using ANSYS software, the researchers used RSM to systematically investigate and discover the best design parameter combinations that optimize deformation and reduce mass. This draws on the fundamental principles of material mechanics and Finite Element Analysis (FEA), ensuring that the design fits both functional and structural requirements. When compared to traditional topology optimization techniques, RSM outperforms them in dealing with multi-objective issues and capturing complex trade-offs like the link between deformation and weight.

Adaptive design is the goal for most robotic grippers. This paper introduced a new design based on response surface optimization provided by ANSYS 18.1 software. The lightweight adaptive robotic gripper based on complaint-mechanism topology optimization was developed in [26] and that was the model to compare our results. The proposed design is shown in Fig. 1. The concept is based on a 2D sketch with a specific set of parameters. These parameters are analyzed to obtain the optimal values that guarantee the lightweight of the finger and the optimum flexibility for grasping objects. Table I shows the parameters and the values.

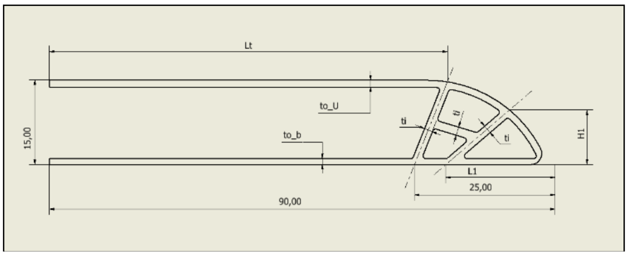


Fig. 1. The proposed design of the adaptive finger (all dimensions in mm).

TABLE I. Design Parameters of the Adaptive Finger

Name	Description	Lower bound (mm)	Upper Bound (mm)
ti	The thickness of the inner frames	0.5	2.5
to_u	The thickness of the upper outer frame	0.5	2.5
to_b	The thickness of the bottom outer frame	0.5	2.5
Lt	Length of the top outer frame	70	83
H1	Indicates the angle of the frame near the gripping end	6	10
L1		11	23

The analysis employing response surface optimization starts with a static structural assessment of the initial finger design illustrated in Fig. 2. The force is set to be 14 N according to the physical test done [26]. The lower left points of the fingers were constrained to move in the direction of the force application line (towards the left horizontal). The first step in the analysis performed in this paper is to study the effect of the thickness on the flexibility of the finger structure. This takes place by defining the design of the experiment parameters which are ti, to_u, and to_b.

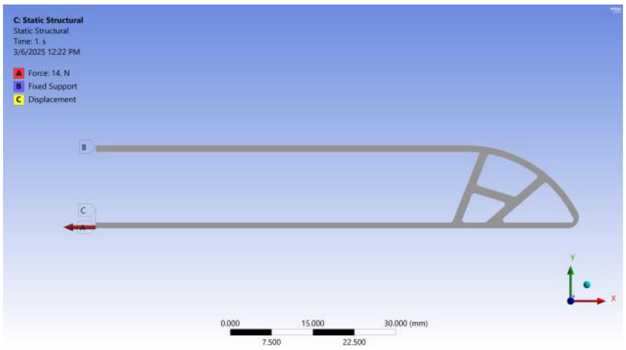


Fig. 2. Definition of load and boundary conditions.

According to limits and several parameters, 15 design points were generated to be the base of formulating the response surface of the design case. The design points include a variance of combinations to cover the whole range of parameter limits. Analyzing the response curve generated after solving the design problem each time with the load and boundary conditions defined before according to a set number of objectives.

The analysis reveals that the to_u (The thickness of the upper outer frame) is the primary sensitive factor influencing the deformation and stress within the finger structure. Fig. 3 shows the sensitivity of the thickness parameters. The parameter to_b (The thickness of the bottom outer frame) has less effect on the deformation and stress values while the ti does not affect them. As a result, it is advisable to exclude this parameter from the analysis to conserve computational time. The value of ti (thickness of inner frame) is set to be 1.5 mm according to the best of the candidates' points that appeared in the analysis.

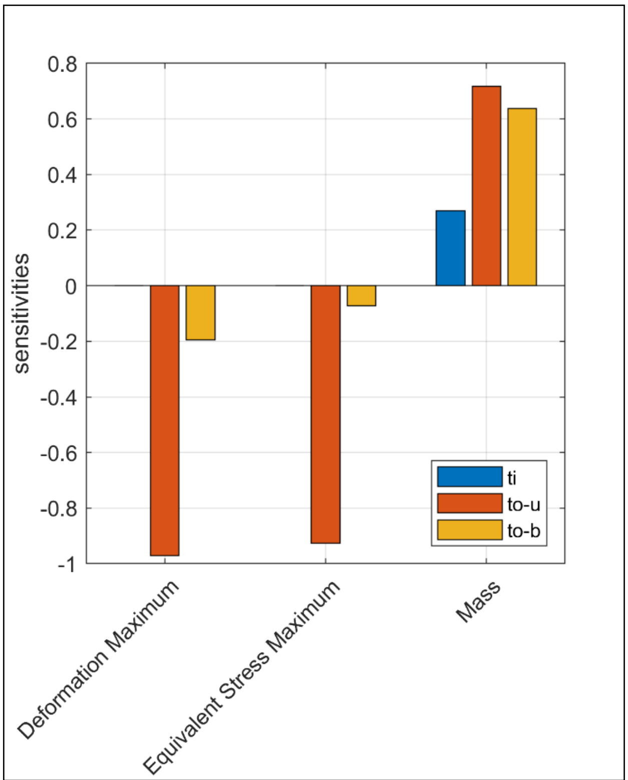


Fig. 3. Sensitivity analysis of initial DOE includes the ti, to_u, to_b parameters.

As a result of the above, more parameters must be added to identify the deformation and stress values to reach the optimum design of the Finger structure. The new parameters of the new optimization are to be the same as in Table I excluding the ti (thickness of inner frames) parameter.

Now, five parameters are included in the analysis, which means that the set of design points in the DOE will be increased. The DOE set points are increased to 27, each point has a set of values for the DOE parameters. For example, point 13 has (1.9625, 1.5375, 74.658, 7.433, 15.3) mm values for (to_u, to_b, Lt, H1, L1) respectively. The response curves are constructed between each parameter and the output variables. to_u vs. deformation is an example shown in Fig. 4.

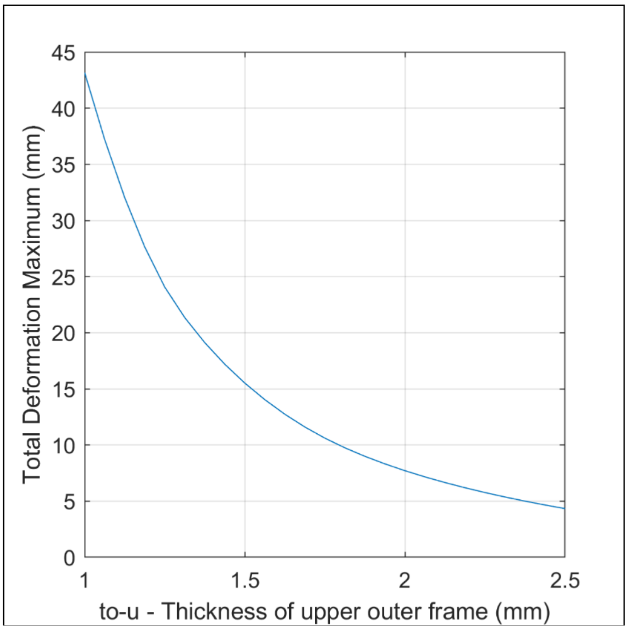


Fig. 4. Response cure of total deformation (max) to the change in the outer upper frame thickness.

Fig. 4 shows the limits of parameters on the x-axis and the deformation values on the y-axis, and the increase of the outer upper frame thickness causes the deformation to decrease which we don't need to happen. This curve is sometimes called the learning curve which allows the software to learn the behavior of response of the parameter and to expect the values along the curve constructed. Each parameter has its response to the output parameters. The values of the total deformation and mass (which is the output parameter) are based on the PLA material which is widely used in 3D printing facilities. Material density is 1.24 g/cm^3 which is relatively low to give the required lightweight of the gripper.

Now the system learns the behavior of the design and is ready to input the optimization values needed. Usually, the RSM procedure learns the behavior of the system by gathering the design of experiment DOE data, fitting a mathematical model to the data, and then using the model to forecast the output response for various input settings. This method is especially beneficial when working with complicated systems in which the relationship between inputs and outcomes is not obvious, or when performing experiments is expensive or time-consuming [30, 31].

In this paper, two main goals are to formulate the input parameters of the optimization phase of this study. The first goal is to set the deformation to be maximized to give more flexibility to the finger of the robotic gripper, this flexibility raises the ability to grasp things in different shapes properly. In addition to the first goal, a constraint was added to ensure that the maximum deformation not to be more than 40 mm. The value is from reasonable logic and controls the flexibility behavior of the finger. The second goal of this study is to minimize the mass of the figure as much as possible. Because the mass is an important parameter that affects the behavior of the gripper.

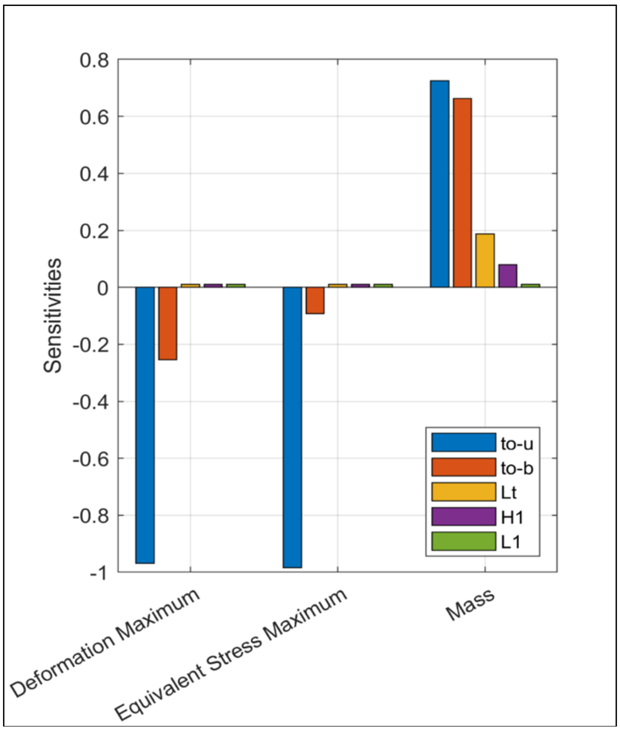


Fig. 5. Sensitivity response of design parameters.

As shown in Fig. 5, the main effect on the design output parameters arises from the thickness of the outer upper frame to_u, which is the main in deformation and stress values. In Fig. 5, the to_b and H1 parameters have a slight positive effect on the desired goals. the thickness parameters have the most control over finger structures' mass values and the rest parameters have a very weak behavior attitude on mass values.

Another important step in the RSM is the trade-off curve in response surface optimization is the graphic depiction of the connection between several objective functions. It demonstrates the trade-offs that arise while maximizing a system regarding several goals. The curve illustrates the necessary trade-off between opposing goals, when achieving one goal may result in the degradation of another [30].

The trade-off between the deformation and the mass are shown in Fig. 6. The curve is based on 1000 sample to meet the maximum deformation and minimum mass goals, the curve shows as the deformation increase the value of mass decreases exponentially.

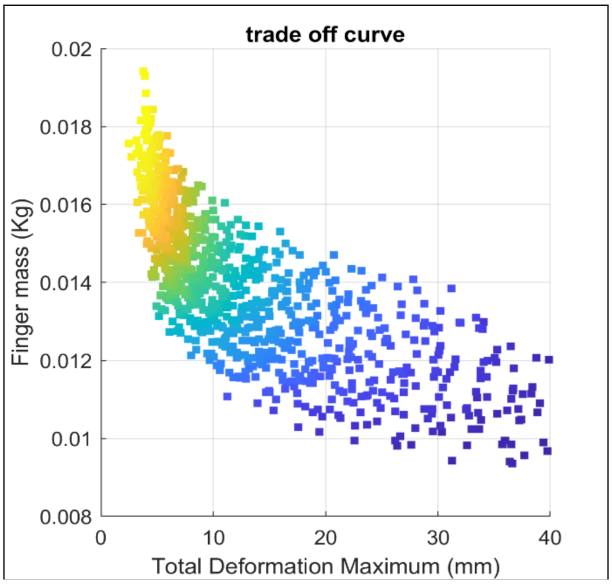


Fig. 6. Trade-off between outputs (deformation and mass).

After investigating the response surface of the system, 1000 samples were selected to formulate the goal behavior that was needed. Three points are selected to be the most significant points that satisfy the goal sought. For the current design, the candidate points, and their verification are shown in Table II. The selected points are validated after that to ensure the goals are well satisfied.

Based on the results above, candidate point 3 which has 1.217, 1.053, 70.862, 9.688, 19.403 mm values for to_u, to_b, Lt, H1, L1 respectively was selected to set as the final design or optimum design upon the goals described above and due to the lower value of the stress generated on it. Table III shows the final values of the design parameters to use in the validation of the results. The table shows that some parameters are near the lower limit while others are near to average value of the range. This variety of values is due to meeting the required objective of the analysis.

TABLE II. CANDIDATES POINTS (THE BEST PERFORMANCE ON THE RESPONSE CURVE)

Name	to_u (mm)	to_b (mm)	Lt (mm)	H1 (mm)	L1 (mm)	Total deformation Max. (mm)	Equivalent stress max. (MPa)	Mass (Kg)
Candidate Point 1	1.151	1.223	75.356	6.13	14.505	39.750	31.079	0.009674
Candidate Point 2	1.181	1.177	72.146	6.77	13.525	36.617	29.292	0.009354
Candidate Point 3	1.217	1.053	70.862	9.688	19.403	37.416	27.993	0.009411

TABLE III. MODIFIED VALUES OF DESIGN PARAMETERS

Name	to_u (mm)	to_b (mm)	Lt (mm)	H1 (mm)	L1 (mm)	Total deformation Max. (mm)
Candidate Point 1	1.151	1.223	75.356	6.13	14.505	39.750
Candidate Point 2	1.181	1.177	72.146	6.77	13.525	36.617
Candidate Point 3	1.217	1.053	70.862	9.688	19.403	37.416

By adding the mounting points to the finger, the final design will be as shown in Fig. 7.

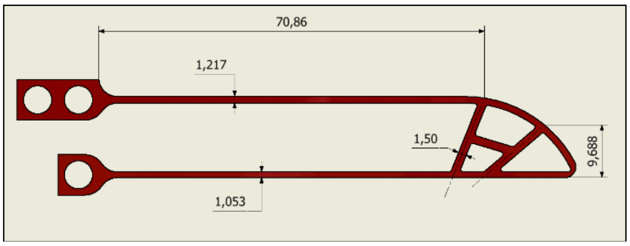


Fig. 7. Final design of the gripper finger (all dimensions in mm).

B. Design of Gripper Base

As mentioned above, the topology optimization used in [26] is sufficient for the gripper base so the design is inspired from that. A new feature was added to the design to complete the four-finger gripper base. Fig. 8 shows the base design with finger installation points.

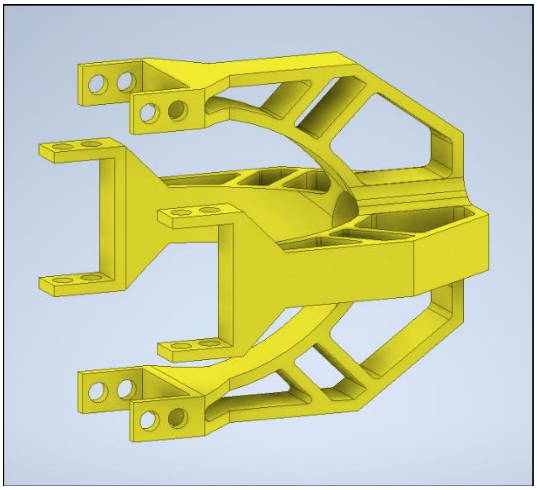


Fig. 8 Improved design of the lightweight gripper base.

IV. Results and Discussion

The bending phenomenon can be observed in the FEM-simulated deformations in Fig. 9. The bending of the finger shows that the tip of the finger moves around 37 mm from its original position. This is what was mentioned earlier about the flexibility of the finger to increase the grasping ability of the gripper. Compared with [26] results the finger flexibility in this paper is highly competitive. The stress results are shown in Fig. 10. It is clearly shown that the stress values of the finger are 32 MPa, which is slightly higher than its counterparts in [26]. The stress value of the finger is still relatively low compared to the yield stress of the material used in printing PLA. Fig. 10 displays stress values obtained after validating candidate point 3 mentioned in Table II. The difference in stress values is due to the different mathematical solutions generated by the response surface method and the solution method used in the static structural workbench of the Ansys software.

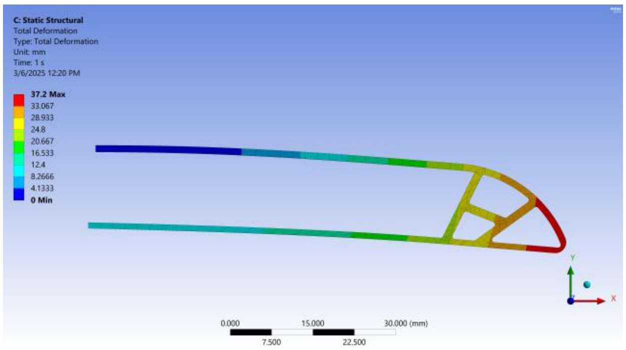


Fig. 9. Bending simulation of adaptive finger (mm).

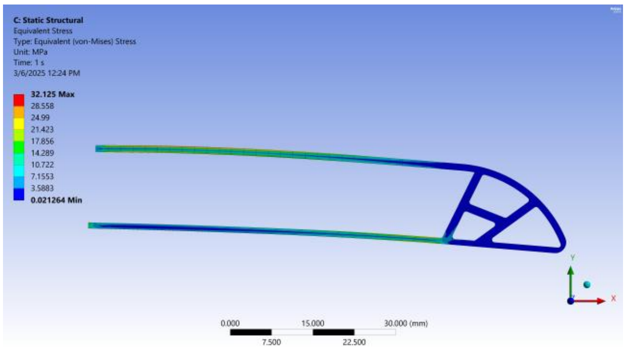
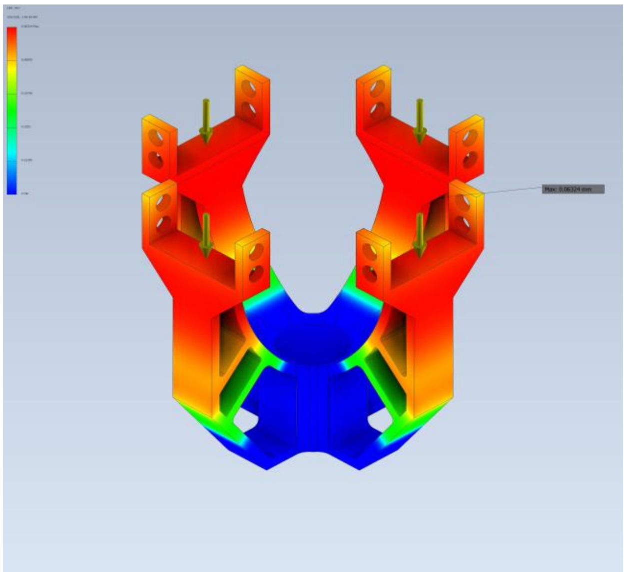
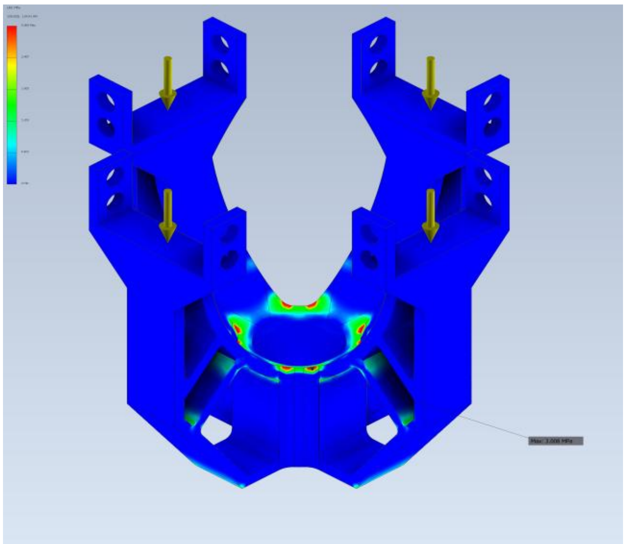


Fig. 10. Stress distribution in adaptive finger (MPa).

When the gripper base structure is subjected to force equal to the reaction from the finger structure at the fixing points an equivalent stress and deformation will appear. Fig. 11(a) shows the total deformation of the gripper base. The maximum value is 0.06324 mm which is infinitesimally small compared to the base size. Fig. 11(b) shows the equivalent stress on the base. The value of the stress is 3 MPa, which is a very small value to exert a risk on such a base. We conducted weight measurements on the design, revealing a final mass of 10 g.



(a)



(b)

Fig. 11. Gripper base simulation results. (a) total deformation on the base. (b) stress distribution on the base.

In terms of technological accuracy, the suggested lightweight adaptive gripper makes use of advanced response surface optimization techniques, which are increasingly recognized for their accuracy in optimizing multi-objective engineering problems. Compared to classic topology optimization methods, as highlighted in recent works [26], this methodology allows for a more extensive investigation of the trade-offs between deformation and mass, resulting in a design that is both flexible and lightweight. Furthermore, the use of ANSYS tools, such as Response Surface Methodology (RSM) and Design of Experiments (DOE), propels this study to the forefront of computationally driven design techniques. In comparison, current research on robotic grippers, such as Elangovan *et al.*'s multi-modal adaptive gripper [27], displays similar innovation by focusing on reconfigurability and flexibility. Unlike prior research, such as Sun *et al.* [26], where the adaptive gripper weighed 180 g and handled a payload up to 8.8 kg, our design, however, achieves a significant mass reduction to 10 g while maintaining a maximum deformation of 37 mm. These comparisons demonstrate how well the suggested optimization strategy works, providing a reliable and lightweight solution appropriate for a variety of uses. For even wider applicability, future versions might incorporate more performance indicators like durability and energy economy.

The optimization problem in this work is to create an adaptive lightweight robotic gripper with minimum mass and maximum deformation using response surface optimization techniques. However, the proposed approach's uniqueness and effectiveness must be highlighted by using advanced optimization approaches and conducting a theoretical comparison with current studies. Nguyen *et al.* [33] created a formation control technique that employs reinforcement learning, demonstrating the potential to optimize complex systems utilizing adaptive control procedures. Similarly, Chen *et al.* [34] used actor-critic learning for adaptive optimal formation control, stressing robust optimization with assured performance, which is theoretically consistent with our goal of robust and efficient gripper design. Furthermore, Tran *et al.* [35] investigated a Model Predictive Control (MPC) technique, which shows substantial promise for regulating autonomous systems under various constraints and provides insights into constraint-handling mechanisms. Saenrit and Phaoharuhansa [36] use modified Gaussian potential functions for obstacle avoidance, demonstrating the adaptability of optimization strategies to obtain precision in dynamic contexts. Finally, Van *et al.* [37] created a hierarchical sliding mode control model that provides a framework for ensuring stability and precision in systems with multiple degrees of freedom. These studies serve as a comparative backdrop to our methodology, highlighting how response surface optimization provides a structured way to achieving optimal trade-offs, as illustrated by the trade-off curve in Fig. 6 Incorporating these methodologies and studies not only emphasizes the importance of optimization strategies, but also lays the groundwork for future advancements in adaptive gripper design.

V. Conclusion and Future Works

In response to the need for soft grippers capable of handling objects of various sizes without complex mechanisms or additional components, this paper presents an innovative and lightweight design for an adaptive gripper. During the design process, ANSYS software was used to enhance the bending performance of the gripper by optimizing its response surface characteristics. The discussion will focus on the suggested design process, the efficiency of the optimization process, and any potential consequences.

An overview of optimization techniques, such as response surface optimization and 3D topology optimization were the first steps in the design process. Response surface optimization aims to obtain the optimal combination of input parameters to achieve a specific desired outcome. The optimization approach in this study was aided using ANSYS software tools including Response Surface Methodology (RSM) and Design of Experiments (DOE). Initial parameters were generated from prior research and examined to see how they affected the flexibility and stress of the finger structure to develop an adaptable finger design. The most sensitive parameter is to_u (thickness of the outer frame), impacting deformation and stress, which was emphasized on the response surface created by the research. To further improve the design, more factors were subsequently added to the optimization process. An illustration of the trade-off between deformation and mass was derived using response surface optimization. The selection of an ideal design was based on candidate locations obtained from the response surface analysis to maximize deformation while reducing mass. Additionally, topology optimization from prior research served as inspiration for the gripper base design, which included additional characteristics to complete the four-finger gripper base.

In summary, our study developed a novel procedure utilizing the response surface method which produces a modified design for a lightweight adaptive gripper. The optimization method made it possible to pinpoint the ideal settings for improving the gripper's ability to bend. The suggested design met the objectives by increasing deformation and decreasing mass. The trade-off curve showing the link between mass and deformation provided conclusive proof of the success of the optimization procedure. Candidate points were found by carefully examining the response surface, which allowed the best design to be chosen. The final mass of the design is 10 g which is relatively low compared to other designs found in literature.

In response to the increased demand for creative solutions in robotics and automation, our research successfully provided an inventive and lightweight adaptive gripper design that was refined using advanced optimization techniques. This paper now shifts its focus to the horizon of future possibilities, diving into new research avenues and practical applications that can expand on our fundamental work. One is to examine the possibility of incorporating the adaptive gripper into robotic systems for applications such as pick-and-place activities in manufacturing, logistics, or healthcare. Investigating issues of human-robot interaction, such as safety and usefulness will improve the value of the gripper. Explore the use of innovative materials, such as shape-memory alloys or composites, to improve the gripper's flexibility, strength, and durability, and conduct material testing and characterization to ensure that the materials are suitable for the gripper's components will improve the quality of the gripper. In our future works, we plan to conduct experimental testing to validate the simulation findings, assess the gripper's performance in real-life applications, and further investigate its capabilities for handling objects of varying sizes.

A. Limitations

While the proposed design has substantial advantages in terms of lightweight structure and increased flexibility, several limitations must be mentioned. For starters, while PLA material is inexpensive and widely available for 3D printing, it may not provide adequate durability under prolonged or harsh loading conditions, possibly limiting its application in heavy-duty industrial environments. Second, the optimization approach is primarily concerned with deformation and mass reduction; other aspects, such as thermal stability or wear resistance, are not explicitly addressed. Furthermore, the study is presently being evaluated using simulations, and real-world testing is needed to establish the gripper's performance in a variety of operational circumstances. Future research should investigate alternative materials, increased performance standards, and experimental validation to solve these limitations.

B. Future Scopes

The proposed adaptable lightweight gripper provides numerous options for future research and development. One viable approach is to use innovative materials, such as carbon-reinforced composites or shape-memory alloys, to improve durability, flexibility, and overall performance under different environmental conditions. Furthermore, incorporating sensing technologies such as force sensors or tactile feedback systems could improve the gripper's precision and adaptability, especially for delicate operations in industries such as healthcare or electronics production. Another potential option is the creation of multi-functional grippers capable of doing tasks other than simple object manipulation, such as assembly or inspection. Expanding the optimization criteria to incorporate energy economy, thermal resistance, and fatigue life can broaden the gripper's applications. Finally, real-world experimental testing and deployment in industrial automation scenarios would give useful insights regarding real performance and guide further refinement of the design.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mohammad Al Mashagbeh conducted the research, analyzed the data, and wrote the paper. Saleh Elayyan was responsible for the mechanical design, writing the paper, and conducting the simulations. Migdad Tamimi enhanced the quality of the paper, particularly through contributions to the simulations. He also played a key role in the review process, including responding to reviewers and addressing all feedback. All authors had approved the final version manuscript.

Acknowledgement

The authors acknowledge the use of ChatGPT [https://chat.openai.com/] to proofread parts of this manuscript.

References

[1] Z. Long, Q. Jiang, T. Shuai, F. Wen, and C. Liang, "A systematic review and meta-analysis of robotic gripper," IOP *Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Apr. 2020. doi: 10.1088/1757-899X/782/4/042055

[2] K. Tai, A. R. El-Sayed, M. Shahriari, M. Biglarbegian, and S. Mahmud, "State of the art robotic grippers and applications," *Robotics*, vol. 5, no. 2, Jun. 2016. doi: 10.3390/robotics5020011

[3] R. A. Romeo, L. Fiorio, E. J. Avila-Mireles, F. Cannella, G. Metta, and D. Pucci, "Closed-loop force control of a pneumatic gripper actuated by two pressure regulators," in *Proc. IEEE International Conference on Intelligent Robots and Systems (IROS)*, Nov. 2019, pp. 7157–7162. doi: 10.1109/IROS40897.2019.8968226

[4] L. Chin, M. C. Yuen, J. Lipton, L. H. Trueba, R. Kramer-Bottiglio, and D. Rus, "A simple electric soft robotic gripper with high-deformation haptic feedback," in *Proc. IEEE International Conference*, IEEE, 2019.

[5] A. D. Marchese, R. K. Katzschmann, and D. Rus, "A recipe for soft fluidic elastomer robots," *Soft Robotics*, vol. 2, no. 1, pp. 7–25, Mar. 2015. doi: 10.1089/soro.2014.0022

[6] Y. Hao *et al.*, "A soft gripper with programmable effective length, tactile and curvature sensory feedback," *Smart Materials and Structures*, vol. 29, no. 3, 2020. doi: 10.1088/1361-665X/ab6759

[7] Y. F. Zhang *et al.*, "Fast-response, stiffness-tunable soft actuator by hybrid multimaterial 3D printing," *Advanced Functional Materials*, vol. 29, no. 15, Apr. 2019. doi: 10.1002/adfm.201806698

[8] P. Polygerinos *et al.*, "Modeling of soft fiber-reinforced bending actuators," *IEEE Transactions on Robotics*, vol. 31, no. 3, pp. 778–789, Jun. 2015. doi: 10.1109/TRO.2015.2428504
[9] Y. Zhou, L. M. Headings, and M. J. Dapino, "Modeling of soft robotic grippers integrated with fluidic prestressed composite actuators," *Journal of Mechanisms and Robotics*, vol. 14, no. 3, Jun. 2022. doi: 10.1115/1.4052699
[10] T. T. Hoang, P. T. Phan, M. T. Thai, N. H. Lovell, and T. N. Do, "Bio-inspired conformable and helical soft fabric gripper with variable stiffness and touch sensing," *Advanced Materials Technologies*, vol. 5, no. 12, Dec. 2020. doi: 10.1002/admt.202000724
[11] Q. Chen, D. Schott, and J. Jovanova, "Conceptual design of a novel particle-based soft grasping gripper," *Journal of Mechanisms and Robotics*, vol. 16, no. 5, May 2024. doi: 10.1115/1.4062647
[12] Y. Sun, Y. Liu, L. Xu, Y. Zou, A. Faragasso, and T. C. Lueth, "Automatic design of compliant surgical forceps with adaptive grasping functions," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 1095–1102, Apr. 2020. doi: 10.1109/LRA.2020.2967715
[13] Y. Sun, D. Zhang, T. C. Lueth, and Y. Liu, "FEM-based mechanics modeling of bio-inspired compliant mechanisms for medical applications," *IEEE Transactions on Medical Robotics and Bionics*, 2020. doi: 10.1101/2020.06.15.151670
[14] S. Yang, Q. Xu, and Z. Nan, "Design and Development of a dual-axis force sensing MEMS microgripper," *Journal of Mechanisms and Robotics*, vol. 9, no. 6, Dec. 2017. doi: 10.1115/1.4038010
[15] A. Hassan and M. Abomoharam, "Modeling and design optimization of a robot gripper mechanism," *Robotics and Computer-Integrated Manufacturing*, vol. 46, pp. 94–103, Aug. 2017. doi: 10.1016/j.rcim.2016.12.012
[16] M. Shim and J. H. Kim, "Design and optimization of a robotic gripper for the FEM assembly process of vehicles," *Mechanism and Machine Theory*, vol. 129, pp. 1–16, Nov. 2018. doi: 10.1016/j.mechmachtheory.2018.07.006
[17] G. Hao, H. Li, A. Nayak, and S. Caro, "Design of a compliant gripper with multimode jaws," *Journal of Mechanisms and Robotics*, vol. 10, no. 3, 2018. doi: 10.1115/1.4039498
[18] Y. Gao, X. Huang, I. S. Mann, and H. J. Su, "A novel variable stiffness compliant robotic gripper based on layer jamming," *Journal of Mechanisms and Robotics*, vol. 12, no. 5, Oct. 2020. doi: 10.1115/1.4047156
[19] V. P. Dinakaran *et al.*, "A novel multi-objective constraints-based industrial gripper design with optimized stiffness for object grasping," *Robotics and Autonomous Systems*, vol. 160, Feb. 2023. doi: 10.1016/j.robot.2022.104303
[20] J. Liu *et al.*, "Simulation data driven design optimization for reconfigurable soft gripper system," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 5803–5810, Apr. 2022. doi: 10.1109/LRA.2022.3155825
[21] G. Dämmer, S. Gablenz, A. Hildebrandt, and Z. Major, "Design of an additively manufacturable multi-material lightweight gripper with integrated bellows actuators," *Advances in Science, Technology and Engineering Systems*, vol. 4, no. 2, pp. 23–33, 2019. doi: 10.25046/aj040204
[22] A. Avder, I. Sahin, and M. Dorterler. (2019). Multi-objective design optimization of robot grippers with SPEA2. *International Journal of Intelligent Systems and Applications in Engineering*. [Online]. Available: http://moeaframework.org
[23] A. Milojević, S. Linß, Ž. Ćojbašić, and H. Handroos, "A novel simple, adaptive, and versatile soft-robotic compliant two-finger gripper with an inherently gentle touch," *Journal of Mechanisms and Robotics*, vol. 13, no. 1, Feb. 2021. doi: 10.1115/1.4048752
[24] Y. Sun, G. Student Member, Y. Liu, N. Zhou, T. C. Lueth, and S. Member, "A MATLAB-based framework for designing 3D topology optimized soft robotic grippers," in *Proc. 2021 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, 2020, pp. 1283–1289. doi: 10.36227/techrxiv.13174751.v1
[25] I.-T. Chi, T. Chanthasopeephan, and D.-A. Wang, "Design of a parallel gripper based on topology synthesis and evolutionary optimization," *Journal of Mechanisms and Robotics*, vol. 14, no. 2, Apr. 2022. doi: 10.1115/1.4052335
[26] Y. Sun, Y. Liu, F. Pancheri, and T. C. Lueth, "LARG: A lightweight robotic gripper with 3-d topology optimized adaptive fingers," *IEEE/ASME Transactions on Mechatronics*, vol. 27, no. 4, pp. 2026–2034, Aug. 2022. doi: 10.1109/TMECH.2022.3170800
[27] N. Elangovan, L. Gerez, G. Gao, and M. Liarokapis, "Improving robotic manipulation without sacrificing grasping efficiency: A multi-modal, adaptive gripper with reconfigurable finger bases," *IEEE Access*, vol. 9, pp. 83298–83308, 2021. doi: 10.1109/ACCESS.2021.3086802
[28] M. P. Bendsøe and O. Sigmund, *Topology Optimization*, Springer, Berlin, Heidelberg, 2004. doi: 10.1007/978-3-662-05086-6
[29] A. I. Khuri, "A general overview of response surface methodology," *Biom. Biostat. Int. J.*, vol. 5, no. 3, Mar. 2017. doi: 10.15406/bbij.2017.05.00133
[30] R. H. Myers, D. C. Montgomery, and C. M. *Anderson-Cook, Response Surface Methodology: Process and Product Optimization Using Designed Experiments*, 4th ed. Wiley, 2016.
[31] ANSYS Inc. (2023). ANSYS Help. Response surface optimization. ANSYS Mechanical. [Online]. Available: https://www.ansys.com
[32] C.-Y. Chou and C.-F. Juang, "Navigation of an autonomous wheeled robot in unknown environments based on evolutionary fuzzy control," *Inventions*, vol. 3, no. 1, pp. 1–12, Mar. 2018. doi: 10.3390/inventions3010003
[33] K. Nguyen, V. T. Dang, D. D. Pham, and P. N. Dao, "Formation control scheme with reinforcement learning strategy for a group of multiple surface vehicles," *International Journal of Robust and Nonlinear Control*, vol. 34, no. 3, pp. 2252–2279, Nov. 2023. doi: 10.1002/rnc.7083
[34] L. Chen, C. Dong, S. He, and S. Dai, "Adaptive optimal formation control for unmanned surface vehicles with guaranteed performance using actor-critic learning architecture," *International Journal of Robust and Nonlinear Control*, vol. 33, no. 8, pp. 4504–4522, Feb. 2023. doi: 10.1002/rnc.6623
[35] N. S. Tran, K. L. Lai, and P. N. Dao, "A novel model predictive control for an autonomous four-wheel independent vehicle," *International Journal of Mechanical Engineering and Robotics Research*, vol. 13, no. 5, pp. 509–515, 2024. doi: 10.18178/ijmerr.13.5.509-515
[36] K. Saenrit and D. Phaoharuhansa, "Development of obstacle avoidance control system using modified attractive equations of gaussian potential function," *International Journal of Mechanical Engineering and Robotics Research*, vol. 13, no. 3, pp. 408–413, 2024. doi: 10.18178/ijmerr.13.3.408-413
[37] T. N. Van, P. D. Van, T. N. Cong, and H. N. Chi, "Modeling and designing hierarchical sliding mode controller for a 4-dof solar autonomous underwater vehicles," *International Journal of Mechanical Engineering and Robotics Research*, vol. 12, no. 5, pp. 275–283, September 2023. doi: 10.18178/ijmerr.12.5.275-283