

PAPER • OPEN ACCESS

Assistive exoskeleton hand glove using soft pneumatic actuators: design optimization

To cite this article: M N El-Agroudy *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **973** 012041

View the [article online](#) for updates and enhancements.

You may also like

- [Flexible and stable grasping by multi-jointed pneumatic actuator mimicking the human finger-impacts of structural parameters on performance](#)
Tianze Hao, Huaping Xiao, Shuhai Liu et al.
- [Single chamber multiple degree-of-freedom soft pneumatic actuator enabled by adjustable stiffness layers](#)
Junius Santoso, Erik H Skorina, Marco Salerno et al.
- [A bio-inspired soft planar actuator capable of broadening its working area](#)
Seyed Mohammad Zeyb Sayyadan and Mohammad Mehdi Moniri



The advertisement features a dark blue background on the left with white and orange text, and a photograph of a woman at a podium on the right. The woman is smiling and looking towards the camera. The text on the left includes the ECS logo, the society's name, the meeting details, and a promotional slogan.

ECS The Electrochemical Society
Advancing solid state & electrochemical science & technology

243rd Meeting with SOFC-XVIII

Boston, MA • May 28 – June 2, 2023

Accelerate scientific discovery!

Learn More & Register

Assistive exoskeleton hand glove using soft pneumatic actuators: design optimization

M N El-Agroudy¹, M I Awad¹, A Rehan¹ and S A Maged¹

¹Mechatronics Department, Faculty of Engineering, Ain Shams University
shady.maged@eng.asu.edu.eg

Abstract. An assistive exoskeleton hand glove can be the solution to people who suffer from impairment in hand functionality. Soft pneumatic actuators (SPA) are used to actuate such glove. This paper focus on optimizing the design of the soft actuator. Finite element (FE) model is linked with the design optimization tool to find the optimal dimensions and materials of the SPA that give maximum displacement of the actuator with acceptable stresses on the actuator's body. Performance analysis shows the relation between different parameters and how each affect the performance of the actuator. Results show the dimensions and materials needed to have maximum actuator displacement without being subjected to high stresses.

1. Introduction

Our hands are of great importance to our daily activities, whether you're a 10-year-old or even 60 years old. Its functionality is irreplaceable. But this functionality can be impaired due to strokes or accidents. Thus, rehabilitation is now needed to restore the lost functionality of the hand. Rehabilitation and physical therapy require the patient to go to a clinic or hospital for up to 6 months to perform specific tasks with certain difficulty that is directly proportional to the improvement in the patient's performance. Such process can be expensive on the long run and time consuming. Also, the need of an assistive device still exists to assist the patient in performing the everyday tasks. Thus, an exoskeleton hand glove is needed.

The glove is designed so that it's actuated with soft pneumatic actuators (SPA). The actuators will tend to move in any direction when inflated. So, the motion must be restricted to give the desired motion. For example, if the actuator is to bend, we need to restrict the other degrees of freedom. Thus, an inextensible layer is added so that the actuator will not be able to elongate. Also, Fibres in both clockwise and anti-clockwise directions are added to restrict the twisting motion. Therefore, the actuator can only bend.

In last decade, many researchers start to model and optimize the parameters of the SPA that is used in the exoskeleton hand glove, like in [1]-[4]. Zhongkui Wang and Shinichi Hirai modelled, simulated and optimized the performance of a soft pneumatic gripper for handling deformable objects [1]. In [2], Gundula Runge, Jan Peters and Annika Raatz modelled and optimized the design of SPAs using genetic algorithms. Also, Panagiotis Polygerinos et al. modelled, fabricated and controlled SPAs that are made of elastomeric and inextensible materials [3]. Gabriel Dämmer et al. presented, in [4], the design and shape optimization of polyjet bellows actuators.

In this manuscript, the SPA is modelled and simulated. The model is linked with a design optimization tool to find the optimal design parameters that give maximum displacement of the actuator without being subjected to high stresses.



This paper is organized as follows: Section 2 presents the finite element model of the soft pneumatic actuator. Section 3 demonstrates the optimization of the design. The optimization results and discussion will be presented in section 4. Finally, concluding remarks will be drawn in Section 5.

2. FE modelling of the SPA

The actuator is designed as a tube with a semi-circular cross-section. The actuator is modelled via a FE modelling and simulation tool called Abaqus [5]. First, the tube is modelled as 3d-deformable part with inner radius of 6.35 mm and outer radius of 7.35 mm [6]. The length of the tube is 95 mm but the cavity inside it is only 85 mm in length (The tube is solid from each side by a length of 5 mm and the rest is cavity), as shown in figure 1. Then, the cables are created by creating another part and running our python script which will draw our cables. Two scripts exist for clockwise and anticlockwise cables. A set of the cables and an instance are added to the assembly. The cables prevent the SPA from twisting. Figures 2 and 3 show both clockwise and anticlockwise cables, respectively. An outer layer of silicon is added around the cables with thickness of 1 mm, as shown in figure 4. Datum planes are created to partition the tube so that the lower 0.5 mm of the tube's lower face can act as a strain-limiting material. The strain-limiting layer prevents the SPA from elongation. Since the SPA now can neither twist nor elongate, the SPA will bend when pressure is applied.

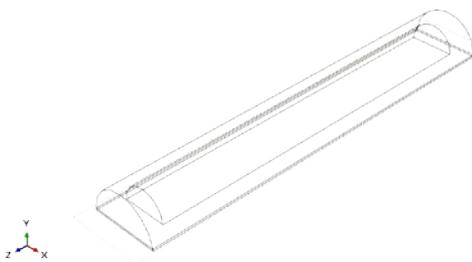


Figure 1. Tube model isometric view.

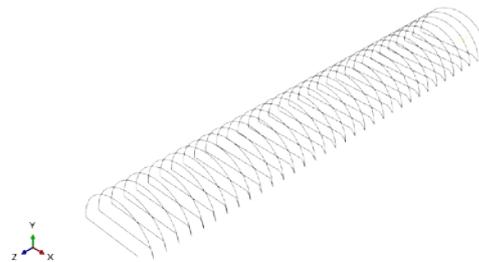


Figure 2. Clockwise cable isometric view.

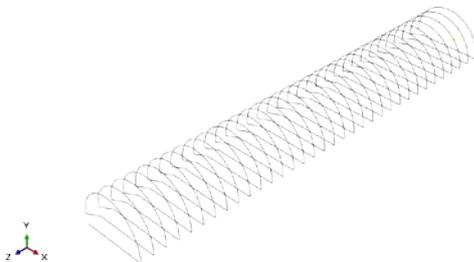


Figure 3. Anti-clockwise cable isometric view.



Figure 4. Outer layer isometric view.

The next step is to create the different materials used in the actuator and assign each material to each of the parts. The materials are dragon-skin 20 [7] for the actuator's upper part, dragon-skin 10 [8] for the outer layer. Fiberglass for the strain-limiting material, Kevlar for the cables. Dragon-skin 20 and Dragon-skin 10 are both modelled as hyperelastic neo-hooke materials. The material is defined with two parameters; C10 and D1, which are temperature dependant parameters, related to shear modulus (μ) and bulk modulus (κ), where $C10 = \mu/2$ and $D1 = 2/\kappa$ [10]. Dragon-skin 20 and Dragon-skin 10 are modelled with C10 coefficients of 0.0316485 and 0.0425 respectively, and D1 coefficients of 0 for both. Fiberglass and Kevlar are modelled as elastic materials with Young's modulus of 72 GPa and 31067 MPa and Poisson's ratio of 0.297 and 0.36, respectively.

Outer and inner surface of the actuator are then defined. Then, a step is created in which we will apply the pressure load. A static general step is selected with minimum increment size of 0.01 and maximum number of increments of 1000. The boundary conditions are then defined by imposing zero displacement on one face of the actuator. Also, an amplitude is created to control the rate at which the pressure load is applied. The amplitude is selected to be equally spaced. Next, load is created of type

pressure and applied to the inner surface that we already defined. The magnitude of pressure is of value 0.03 MPa. This value can be changed anytime to view how it affects the actuator force.

The next step is meshing. After meshing, the cables and the elastomeric tube need to be connected to each other in some way, and this connection is modelled as a ‘tie constraint’, which ties the cables to the surface of the actuator. Another tie constraint is created to connect the outer layer with the tube.

Finally, a job is created and submitted for analysis. Results are viewed and the actuator is functioning as shown in figure 5. The actuator bends and the displacement of any node can be viewed as xy-graph, as shown in figure 6. A node is selected at the actuator’s face and the following graph shows its displacement.

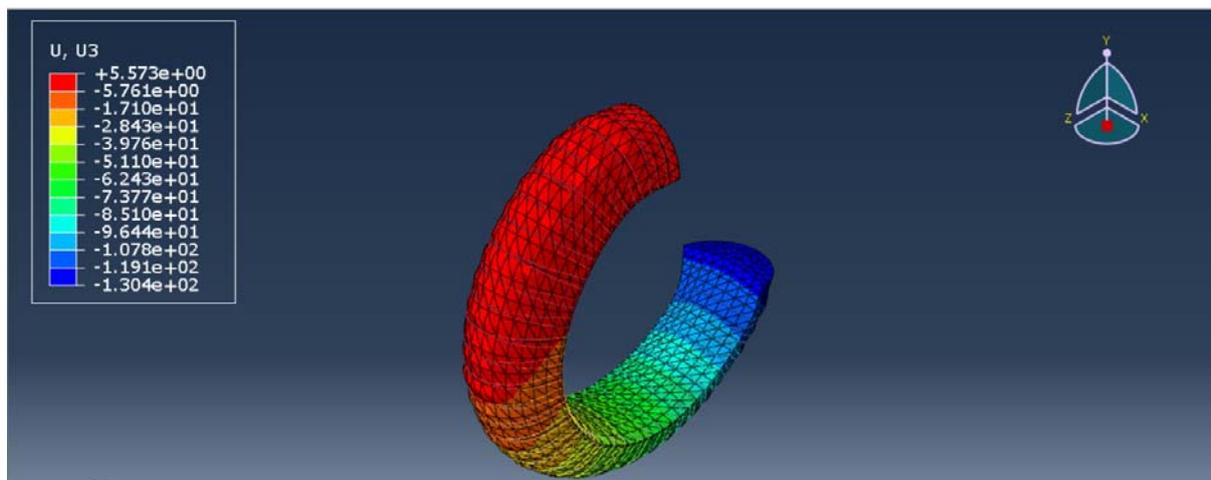


Figure 5. Simulation results and bending of the actuator.

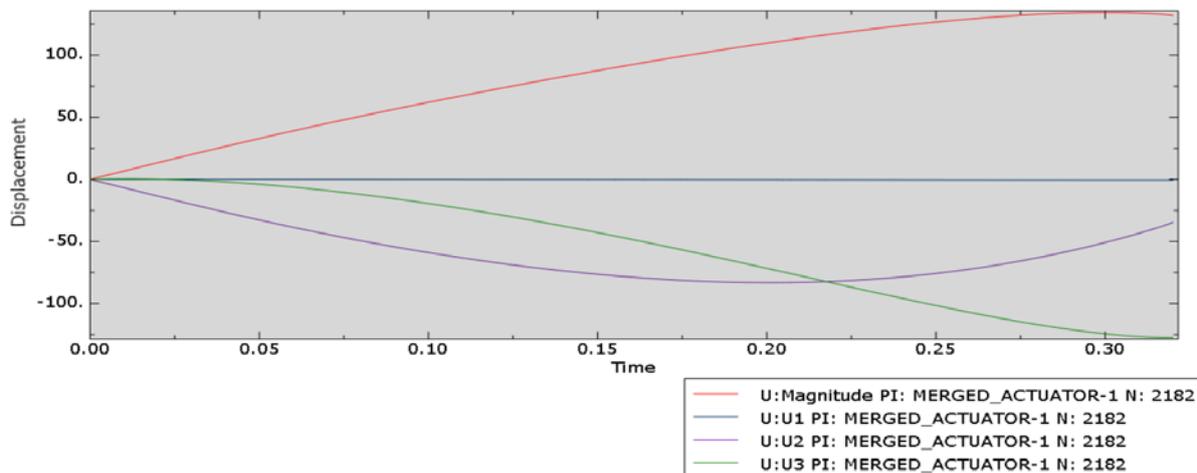


Figure 6. Displacement graph of the actuator.

3. Design optimization of the SPA

After simulation, the maximum stress and the maximum displacement of the SPA are now available. Optimization of the design of the SPA is investigated to reach a higher displacement with acceptable maximum stress. Isight (Dassault System, MA) software tool is used for the optimization problem. Abaqus is added as component. The Abaqus FE job is loaded to select input and output parameters. Neighbourhood cultivation genetic algorithm (NCGA) is selected as the optimization technique [9]. This is a multi-objective exploratory technique. Input parameters (i.e. dimensions, materials, etc.) are results from the optimization and inputs to the Abaqus job. Output parameters (i.e. maximum displacement, maximum stress, etc.) are outputs from the Abaqus job and inputs to the optimization task. The optimization process loop is shown in figure 7.

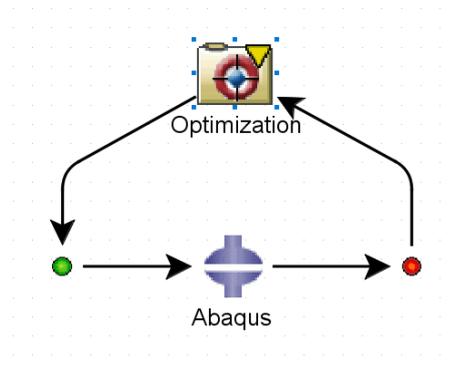


Figure 7. Optimization process loop.

3.1. Dimensional Optimization

The dimensions of the actuator are selected as input parameters. Inner radius and the solid extruded part at the tube's tip are selected and given their allowed values. By changing the solid extruded part's length, the cavity length will change. Inner radius allowed values belong to a discrete set from 4.05 mm to 6.35 mm with 0.1 mm increment, as shown in figure 8. The solid extruded part length allowed values are defined the same way but from 3 mm to 5 mm with 0.1 mm increment. Thus, the cavity length will change from 85 mm to 87 mm with 0.1 mm increment, as shown in figure 9.

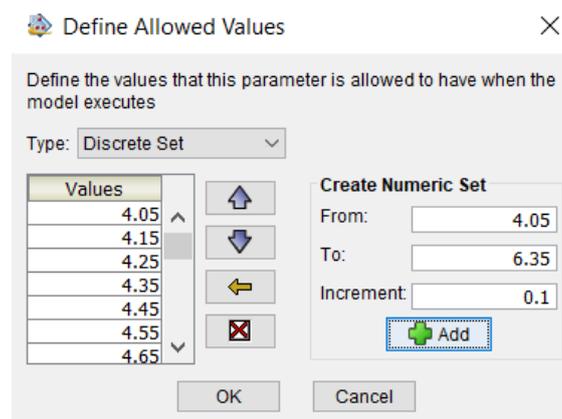


Figure 8. Defining allowed values for the SPA's inner radius.

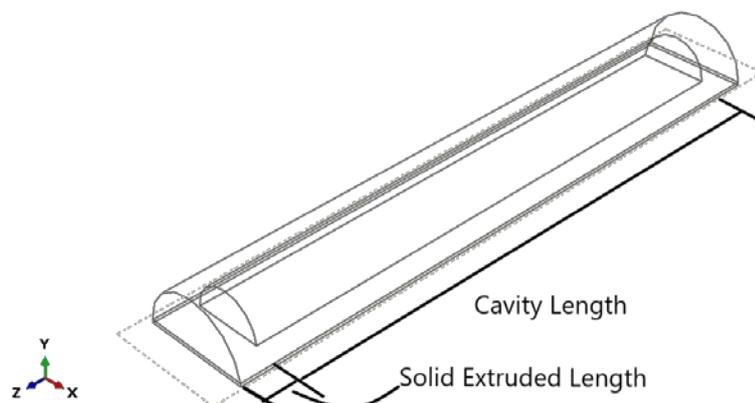


Figure 9. The relation between solid extruded length and cavity length.

The objectives are then specified. The first objective is for the displacement of the most displaced point of the SPA to be maximum. The second objective is for the maximum stress at any point on the actuator to target a value of 450 MPa, as shown in figure 10.

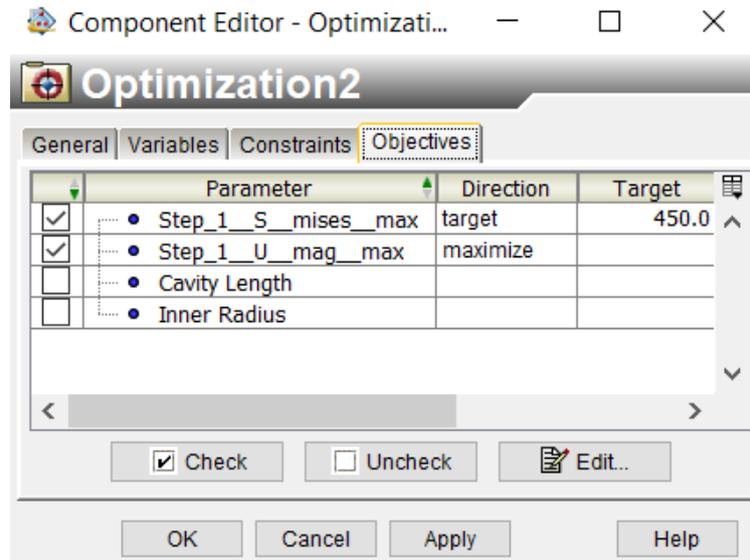


Figure 10. Objective selection.

Another model is also run but with input parameters as inner radius and outer layer thickness. The inner radius has the same allowed values and the outer layer thickness has allowed values from 0.5 mm to 5 mm with 0.5 mm increment. The output parameters and objective functions are the same as the previous model.

3.2. Material optimization

The material of the outer layer and inner layer are optimized by selecting the C10 coefficients of both materials as input parameters. The allowed values are 0.0425 for Dragon-Skin 10, 0.031648 for Dragon-Skin 20, 0.03 for EcoFlex-50 and 0.12 for Elastosil. The objective function is the same as in dimensional optimization model.

4. Optimization results

4.1. Dimensional optimization results

For the first model with inner radius and cavity length as input parameters, the number of iterations and computation time are shown in Table 1.

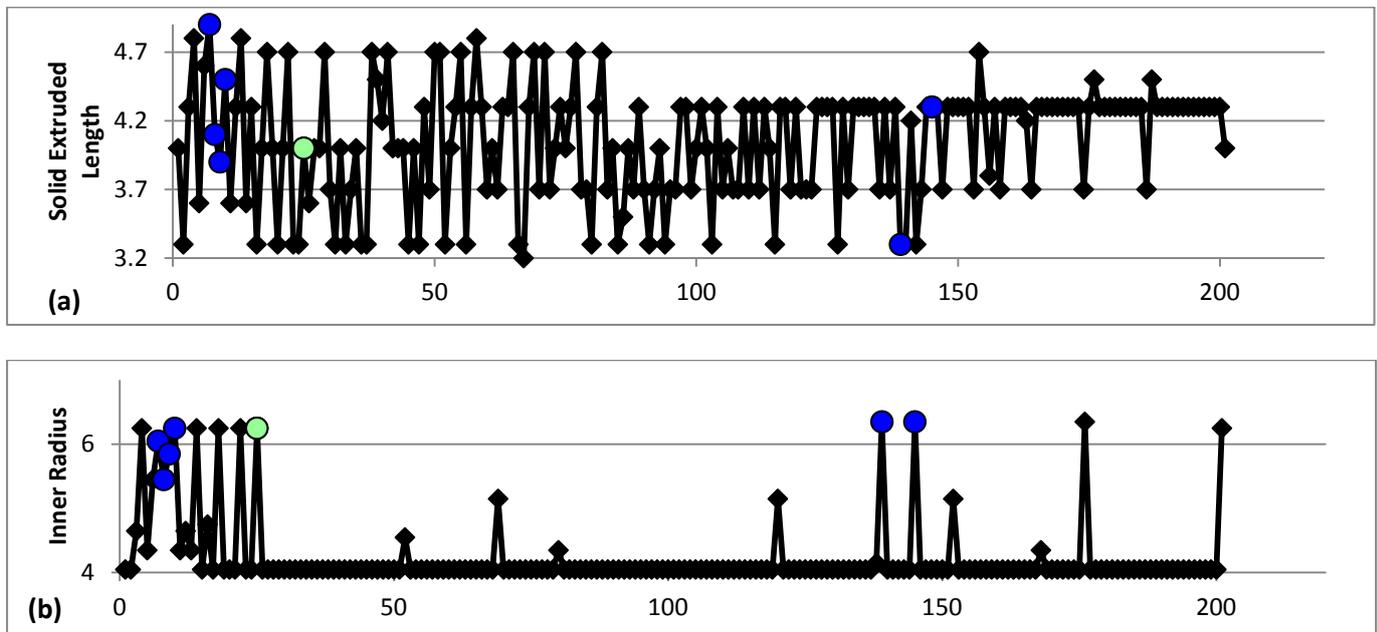
Table 1. Number of iterations and computation time for first model.

Number of iterations	Computation time
201	33 hours

Isight iterated the parameter for 201 times. The best cases results are in light blue and the optimum result is in green. The optimum solution is an inner radius of 6.25 mm and solid excluded length of 4 mm which corresponds to a cavity length of 86 mm. Figure 11 shows a part of the results' Table. It's noticed that the optimum solution corresponds to a maximum displacement of 100.58 and maximum stress of 470.33 Mpa. The best cases are the blue points and the optimum case is the green point. The solid green line in the maximum stress graph represents the target stress value of 450 MPa. Figure 12 shows the optimization results for each parameter.

Run Path		Parameters for all Iterations (Done)							
Iteration	Step	Cavity Length	Inner Radius	Step_1_S_mises_max	Step_1_U_mag_max	Design Feasibility	Objective and Penalty	Objective Function	Penalty Function
1	1	4.0	4.05	239.92	66.645	9	143.23	143.23	0.0
1	2	3.3	4.05	239.44	66.705	7	143.65	143.65	0.0
1	3	4.3	4.65	333.55	80.979	9	35.271	35.271	0.0
1	4	4.8	6.25	592.69	122.45	9	20.04	20.04	0.0
1	5	3.6	4.35	279.46	73.782	7	96.555	96.555	0.0
1	6	4.6	5.45	480.56	100.33	9	-69.969	-69.969	0.0
1	7	4.9	6.05	567.0	116.52	7	0.28517	0.28517	0.0
1	8	4.1	5.45	470.31	100.45	9	-80.338	-80.338	0.0
1	9	3.9	5.85	536.16	111.11	7	-25.151	-25.151	0.0
1	10	4.5	6.25	591.81	122.48	7	19.134	19.134	0.0
1	11	3.6	4.35	333.55	80.979	7	35.271	35.271	0.0
1	12	4.3	4.65	470.31	100.45	8	-80.338	-80.338	0.0
1	13	4.8	4.35	613.5	122.88	7	40.412	40.412	0.0
1	14	3.6	6.25	279.27	73.607	7	96.923	96.923	0.0
1	15	4.3	4.05	238.1	66.659	7	145.05	145.05	0.0
1	16	3.3	4.75	342.45	83.401	7	23.951	23.951	0.0
1	17	4.0	4.05	239.44	66.705	7	143.65	143.65	0.0
1	18	4.7	6.25	277.77	73.719	7	98.31	98.31	0.0
1	19	4.0	4.05	239.44	66.705	7	143.65	143.65	0.0
1	20	3.3	4.05	239.92	66.645	7	143.23	143.23	0.0
1	21	4.0	4.05	239.44	66.705	7	143.65	143.65	0.0
1	22	4.7	6.25	293.03	76.019	7	80.75	80.75	0.0
1	23	3.3	4.05	239.44	66.705	7	143.65	143.65	0.0
1	24	3.3	4.05	239.92	66.645	7	143.23	143.23	0.0
1	25	4.0	6.25	470.33	100.58	9	-80.451	-80.451	0.0
1	26	3.6	4.05	239.92	66.645	7	143.23	143.23	0.0
1	27	4.0	4.05	239.92	66.645	7	143.23	143.23	0.0
1	28	4.0	4.05	239.92	66.645	7	143.23	143.23	0.0
1	29	4.7	4.05	238.1	66.659	7	145.05	145.05	0.0
1	30	3.7	4.05	239.44	66.705	7	143.65	143.65	0.0
1	31	3.3	4.05	252.76	69.138	7	127.9	127.9	0.0
1	32	4.0	4.05	239.44	66.705	7	143.65	143.65	0.0
1	33	3.3	4.05	238.1	66.659	7	145.05	145.05	0.0
1	34	3.7	4.05	238.1	66.659	7	145.05	145.05	0.0
1	35	4.0	4.05	239.44	66.705	7	143.65	143.65	0.0
1	36	3.3	4.05	239.46	66.627	7	143.71	143.71	0.0
1	37	3.3	4.05	239.92	66.645	7	143.23	143.23	0.0
1	38	4.7	4.05	238.99	66.617	7	144.19	144.19	0.0
1	39	4.5	4.05	239.44	66.705	7	143.65	143.65	0.0
1	40	4.2	4.05	239.92	66.645	7	143.23	143.23	0.0
1	41	4.7	4.05	238.99	66.617	7	144.19	144.19	0.0
1	42	4.0	4.05	238.23	66.659	7	144.91	144.91	0.0
1	43	4.0	4.05	239.44	66.705	7	143.65	143.65	0.0
1	44	4.0	4.05	239.44	66.705	7	143.65	143.65	0.0

Figure 11. Optimization results for the first model.



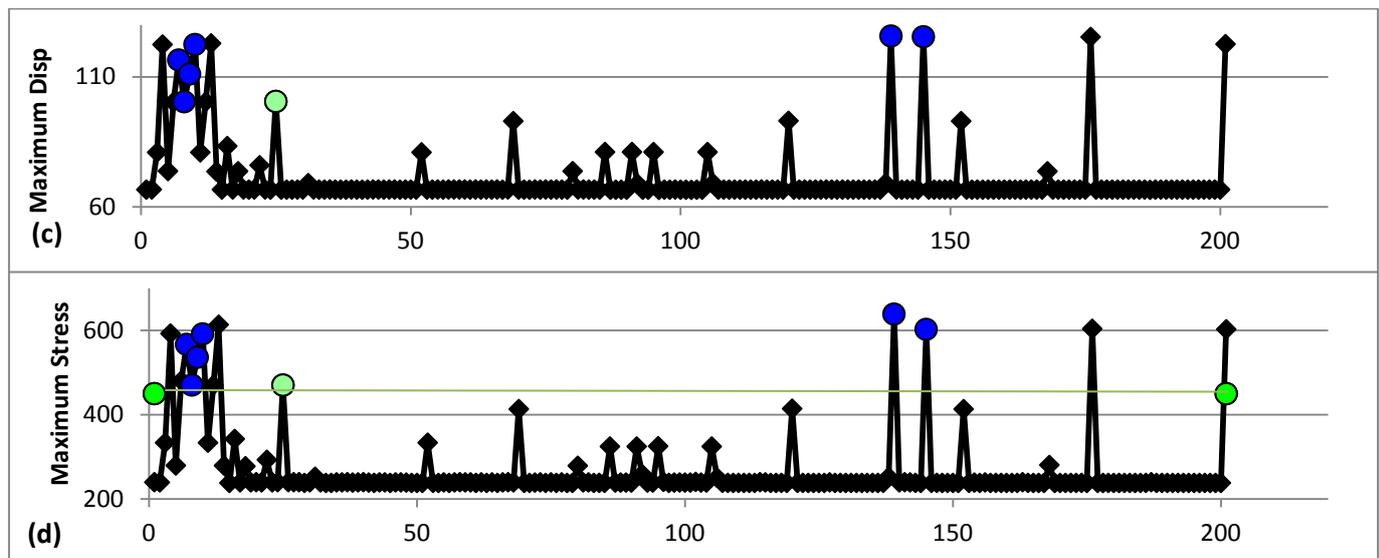


Figure 12. Optimization results of the first model. (a) shows the extruded length values for all points, (b) shows the inner radius values, (c) shows the maximum displacement and (d) shows the maximum stress values.

The linear correlation values between input and output parameters are also extracted. The solid extruded length has low positive correlation with maximum stress and maximum displacement. The inner radius has high positive correlation with both maximum stress and maximum displacement, as shown in Table 2.

Table 2. Correlation Table of first model.

	Maximum Stress	Maximum Displacement
Solid extruded Length	0.114523212	0.115576479
Inner Radius	0.843821803	0.847783115

As for the second model for dimensional optimization with inner radius and outer layer thickness as input parameters, the number of iterations and computation time are shown in Table 3.

Table 3. Number of iterations and computation time for second model.

Number of iterations	Computation time
63	47 hours

The increased computation time is due to the increase in the complexity of the model when the outer layer thickness is changed. The optimum design case is inner radius 5.15 mm and outer layer thickness of 0.5 mm. The corresponding maximum displacement and maximum stress are 66.679 and 433.53 MPa, respectively. Figure 13 shows the optimization process results for each parameter.

It's noted that one of the best cases is point 45 which the same outer layer thickness of 0.5 mm and an inner radius of 6.25 mm which has the same radius obtained from the first model. The linear correlation values between input and output parameters are also extracted. The inner radius has high positive correlation with maximum stress and low positive correlation with maximum displacement. The outer layer thickness and the maximum stress has nearly no correlation and the outer layer thickness and the maximum displacement have high positive correlation, as shown in Table 4.

4.2. Material optimization results

The material optimization process with the inner layer and outer layer materials as input parameters is iterated. Number of iterations and computation time are shown in Table 5.

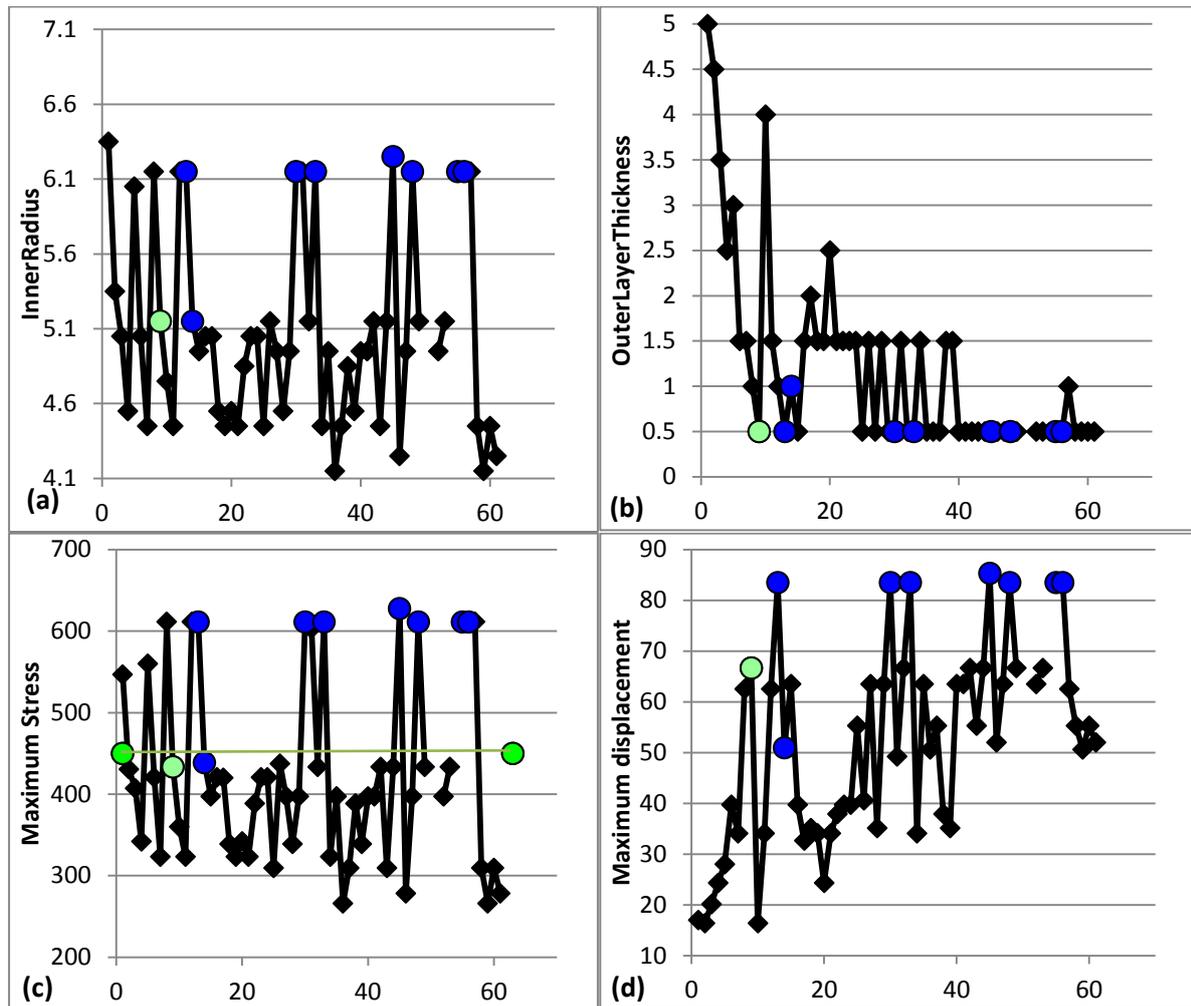


Figure 13. Optimization results of the second model. (a) shows the inner radius values for all points, (b) shows the outer layer thickness values, (c) shows the maximum stress and (d) shows the maximum displacement values.

Table 4. Correlation Table of second model.

	Maximum Stress	Maximum Displacement
Inner Radius	0.991336239	0.443522174
Outer Layer Thickness	-5.47E-04	-0.813641802

Table 5. Number of iterations and computation time for third model.

Number of iterations	Computation time
48	29 hours

The model is to select between the C10 coefficient of 4 materials: Dragon-skin 20, dragon-skin 10, EcoFlex 50 and Elastosil. The optimum design case is dragon-skin 20 for the inner layer material and EcoFlex 50 for the outer layer material. This case corresponds to a maximum displacement of 61.332 and maximum stress of 473.02 MPa. Figure 14 shows the optimization process results.

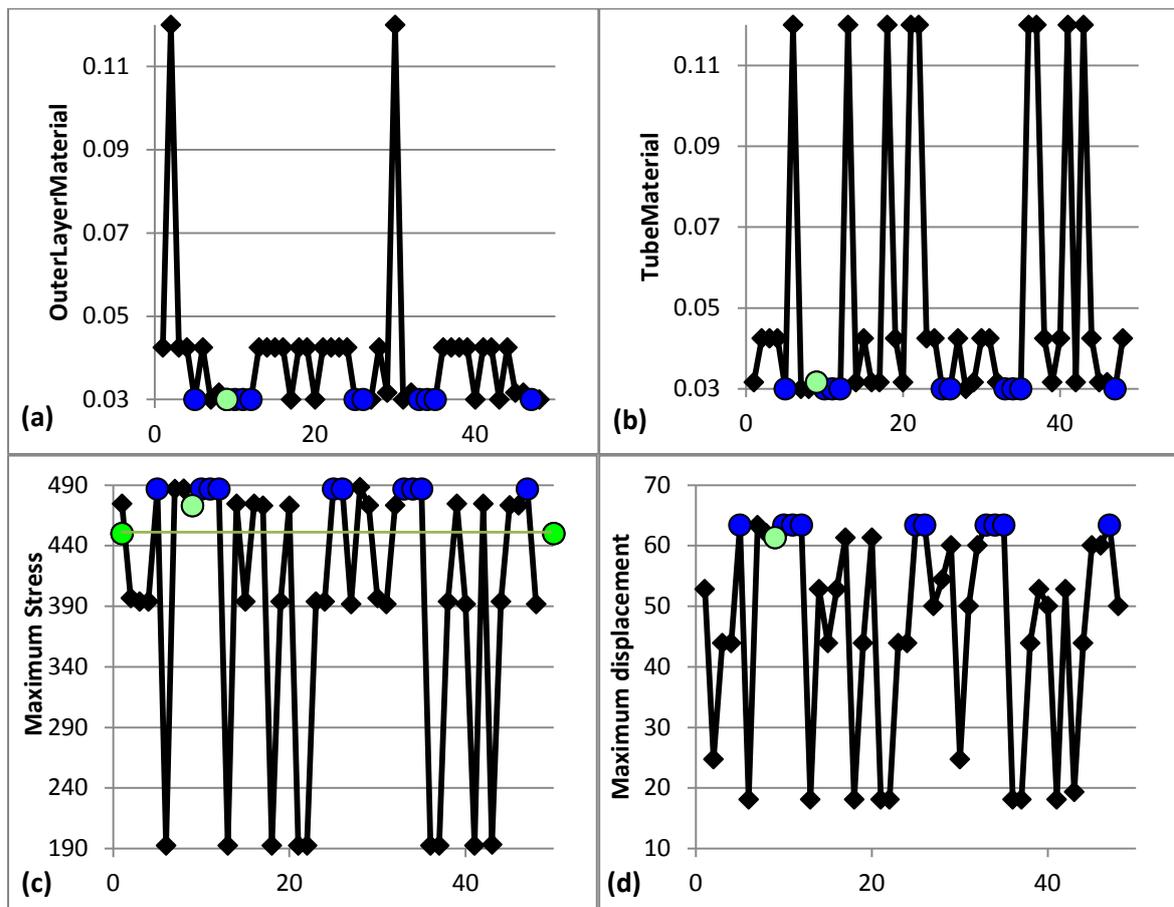


Figure 14. Material optimization results. (a) shows the outer layer material values for all points, (b) shows the inner layer material values, (c) shows the maximum stress and (d) shows the maximum displacement values.

The linear correlation values between input and output parameters are also extracted. The outer layer material has low negative correlation with maximum stress and maximum displacement. The inner layer material has high negative correlation with both maximum stress and maximum displacement, as shown in Table 6.

Table 6. Correlation Table of third model.

	Maximum Stress	Maximum Displacement
Outer Layer Material	-0.176361891	-0.475591571
Inner Layer Material	-0.978232335	-0.897922165

5. Conclusion

The design of the soft actuator can be optimized using an optimization tool that iterates the FE model several times until the optimum solution is reached. I sight optimization tool is used and three models runs are performed. Dimensional optimization results in an optimum inner radius of 6.25 mm, cavity length of 84 mm and outer layer thickness of 0.5 mm. Material optimization shows that the optimum inner layer material is dragon-skin 20 and that of outer layer is EcoFlex-50.

References

- [1] Wang Z and Hirai S 2018 Geometry and Material Optimization of a Soft Pneumatic Gripper for Handling Deformable Object *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pp. 612-617 (Kuala Lumpur Malaysia)
- [2] Runge G, Peters J and Raatz A 2017 *Design optimization of soft pneumatic actuators using genetic algorithms IEEE International Conference on Robotics and Biomimetics (ROBIO)* pp. 393-400 (Macau).
- [3] Polygerinos P et al. June 2015 Modeling of Soft Fiber-Reinforced Bending Actuators *IEEE Transactions on Robotics*, vol. 31, no. 3, pp. 778-789
- [4] Gabriel Dämmer, Sven Gablenz, Alexander Hildebrandt, and Zoltan Major 2018 *Design and shape optimization of PolyJet bellows actuators IEEE International Conference on Soft Robotics (RoboSoft)*Livorno pp. 282-287
- [5] Dassault Systèmes Simulia Corp 2019 <https://www.intrinsys.com/software/simulia/abaqus/why>
- [6] Holland D. P., Berndt S, Herman M, Walsh C 2018 Soft Robotics vol. 5 no. 2 pp. 119-121 *Growing the Soft Robotics Community Through Knowledge-Sharing Initiatives*
- [7] Smooth-on, Inc. 2019 <https://www.smooth-on.com/products/dragon-skin-20/>
- [8] Smooth-on, Inc. 2019 <https://www.smooth-on.com/products/dragon-skin-10-medium/>
- [9] Hiroyasu, Tomoyuki & Miki Mitsunoric 2003 *NCGA: Neighborhood Cultivation Genetic Algorithm for Multi-Objective Optimization Problems*
- [10] Dassault Systèmes Simulia Corp. 2017 <https://abaqus.docs.mit.edu/2017/English/SIMACAEMATRefMap/simamat-c-hyperelastic.htm>