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Optimal design optimization of a hybrid rigid-soft robotic hand using an evolutionary multi-objective algorithm

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***Abstract*— Conventional rigid bodied robotic gripping systems have established their presence in the industrial applications are challenged by the rapid advances in the soft material robotic systems. Soft material robotic manipulators are progressively infiltrating to the market due to their capability of safe interaction with the human operators and objects to be grasped, which leads to the economical operation of the robotic systems. In this study, we presented a geometric model of a hybrid soft-rigid robotic gripper that uses the benefits of both rigid and soft materials. A multi-objective optimal design approach for an under-actuated hybrid soft-rigid three fingers with three phalanges in each finger actuated by tendon is introduced to find the optimum grasping condition using improved multi-objective antlion optimization algorithm (I-MOALO) evolutionary algorithm. A mathematical model is formulated to find the contact forces of the proposed robotic hand while grasping the object followed by the development of the two fitness functions and several geometric constraints incorporated into the proposed model. The obtained Pareto optimal fonts by solving the proposed gripper optimization model using I-MOALO is analyzed by a designer to select the optimal design parameters and also present a significant relation between the objective function and design variables. Sensitivity analysis of the system is conducted to verify the effect of the design variables with the change in the systems.**

I. INTRODUCTION

Early robotic automation is developed to automated hazardous and repetitive work to perform with a higher speed and accuracy. A key role is played by robotic gripper in automatic grasping which is a complex area of robotic automation as grippers need to be designed for a unique and pre-specified work in the industrial applications for enhancing the capability of the systems considering the nature of the workpiece such as weight, size, materials, surface properties, and shape of the object. It is crucial to choose the best gripper in the industrial automation systems for ensuring economic viability. Nature of the job plays a vital role while selecting a gripper for the automation process like vacuum gripper are most efficient while doing the rapid loading or unloading whereas finger type gripper used for the automation process accuracy is more.

In the past few decades, due to the rapid technological advancement in the areas of material developments, soft fabrics, shape memory alloys, carbon fiber, and smart fluids, more robust robotic systems are introduced in the manufacturing processes. For decades, robots have been used in a restricted environment without the interference of human beings is now shifting focus towards the use of collaborative robots in human environments [1]. Collaborative robots have been used alongside the human operator, so it is necessary to provide softness to the robotic gripper to avoid injury and also provided enough rigidity for the stable grasping of the object. Advancement in fabrication methods leads to the production of less cost soft materials [2]. Nature plays a vital role while developing the soft robots by taking inspiration from the different morphologies available like fin ray inspired gripper [3], octopus's tentacle inspired soft robot arm [4], Manduca sexta [5], bird's beak [6] and foot [7] and much more. Apart from the rigid and soft manipulator, there is a space for the hybrid manipulator consists of soft and rigid material similar to the human hand made up of rigid bone and soft skin. The most famous robotic gripper that developed using soft and rigid material is iRobot-Harvard-Yale (iHY) hand [8], and Yale open-source robot hand [9]. Though some of the existed robotic grippers consist of rigid and soft material, only the joints are made of soft materials. The main drawback of the existed grippers has the intricate design and high development cost due to which it is not adequately explored. Rigid actuators have the benefit of accurate motion, and superior exerted force. At the same time, soft actuator displays a higher degree of freedom, and better compliance, but lags in the exerted force.

Due to the abundant and diverse nature of the application of the emerging technology such as the soft robot, and fabric-based pneumatic robot, there is a need for the optimization of their design parameters to meet the desirable demand. From the literature survey, it was found that there is no framework developed for the optimization of the soft robot and hybrid soft-rigid manipulator best to the knowledge of the author. The robot designer able to design the soft robot based on their awareness gained while working with rigid robots as well as trial and error methods. A new type of hybrid robotic hand is presented considering both hard and soft materials to overcome the existed limitation of hard and soft material robotic hand. The proposed design of the hybrid soft-rigid robotic hand able to overcome the existing limitation to allow

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a more improved and robust performance while grasping the objects.

II.OVERVIEW OF PREVIOUS WORK

An exhaustive survey conducted to find the research status, and the existed development on the robotic gripper and optimal design optimization have been undertaken. We categorized the study into four categories, such as rigid, soft, hybrid robotic gripper, and optimal design optimization.

A. Rigid Gripper

Industrial grippers have been developed using rigid materials for grasping the object in the automation systems for decades. Around 99% of the material handling operation in the robotic automation systems uses two-finger rigid robotic gripper due to its simple design and inexpensive [10]. The fabrication process of the traditional rigid grippers has its disadvantages because of their heavyweight and difficult for a machine that leads to less use in the collaborative environment. Some of the well-known dexterous hand available which able to mimic the human hand are the KIST Hand[11], KITECH-Hand [12], and the Robonaut R2 Hand [13].

B. Soft Gripper

In the recent past, a collaborative robot has been introduced to work along with the human operator within the working environment. The primary safety is to maintain an interaction among human operators and robotic environments. While the existed rigid robot able to give the higher precision and repeatability, due to their high masses and rigid structures not fit to work with the human being. For avoiding the accidents between the human and robots are parted by a barrier to prevent the injuries. The above issue linked with the rigid robot can be excluded using the soft coat at the surface so that the interaction between the human and robot is much safer. However, this method is not always realistic to implement. In the recent past, there has been a momentous growth in the development of soft materials, which can be used as the alternative to the rigid structure.

Soft robotics has gain momentum in recent years because of its inherent nature like lightweight, high compliance, and less cost [14]. Though soft material robots have so many advantages, it inherent some of the disadvantages such as limitation prone to the high repeatability work, the fabrication process is more complicated compared to that of the rigid structure, may face the ruptures while working if not appropriately fabricated. Due to the high compliance nature, soft robot bends along with the shape of the object to grasp the object when the pneumatic pressure supplied to the soft robot. Particle jamming of the granular material can improve the stiffness of the soft robot and is applied in a few of the articles to grasp a wide variety of objects [15]. Passive particle jamming is used instead of vacuum jamming [16] for stiffening the soft gripper. Tendon-driven mechanism [17] also used to actuate the soft robotic gripper to make the system less complicated. However, the capacity of the device reduced compared to the traditional pneumatic soft gripper. However, it is a very challenging work to precisely investigate the limitations related to soft robots such as repeatability, sustainability, and higher precision work in a single design of the soft actuator.

C. Hybrid Gripper

The hybrid robotic hand can access the benefits of both rigid structure and soft materials. The human hand is unmatched in grasping with its counterpart in grasping due to its sophisticated vision and tactile senses known as the embedded intelligence. Although the vision system is sufficient for a proper grasping, the tactile sensor can be fruitful, where vision fails to succeed. A human being able to know when the object may slip by its tactile sense, and it adjusts its position for securing the grasp. So sensor integration to the underactuated hybrid gripper will give an advantage during grasping. The hybrid robotic hand lies in the middle of the rigid and soft materials. This kind of hybrid manipulator takes inspiration from the human hand, which shows exceptional dexterity while grasping the objects. Pisa/IIT Hand [18], and iHY Hand [9] are the example of the hybrid manipulator.

D. Optimal Design Systems

Numerous approaches have developed to address design optimization for robotic applications. Traditional techniques such as Min-Max [19, 20], and Sequential Quadratic Programming [21] has been implemented to optimize the proposed gripper design. Although the conventional methods are capable of solving the gripper design problem, it also faces a challenge regarding computational time and accuracy. To overcome the problems mentioned above, soft computing methods are employed in the gripper design optimization problem to obtain the most suitable gripper configuration. Andrzej and Krenich [22-24] developed a multicriteria optimization method of a two-finger robotic gripper to find the optimal parameters. They used a genetic algorithm to address the constraints problem with several objective functions. Datta and Deb [25] addressed the issue considering two different configurations, and each configuration with two objectives functions with constraint equations. Datta et al. [26] proposed a new design optimization problem of the gripper configuration, considering the voice actuator. Their proposed system is developed considering several actuators arranged in parallel and series configuration. Teaching Learning-Based Optimization algorithm (TLBO) is introduced by Rao & Waghmare [27] for solving the gripper design optimization. The soft robot is a very new field of research that lags in the area of optimal analysis is addressed in this study to optimize the design of a hybrid soft-rigid robotic hand. Our objective in this work is to find an appropriate relation between the forces and utilize the I-MOALO algorithm to optimize the design of a tendon driven three-finger robotic hand.

III. MATERIALS AND METHODS

In this section, we presented and discussed the design motivation considered for the development of the hybrid soft-rigid robotic gripper. The human finger is regarded as the primary source of motivation for the design of the proposed hybrid finger as it is present in the middle of the design space between soft and rigid fingers. Rigid grippers can generate higher force and do the precision work, whereas grippers developed from the soft materials have better compliance and a higher degree of freedom. By taking advantage of both the rigid and soft material, a hybrid soft-rigid robotic gripper can develop, which can generate higher force, good compliance, higher DOF, and able to do more precise work. A schematic diagram is illustrated to show the presence of hybrid soft-rigid robotic gripper in the middle of the unexplored design space between rigid and soft gripper, as presented in Figure 1 .

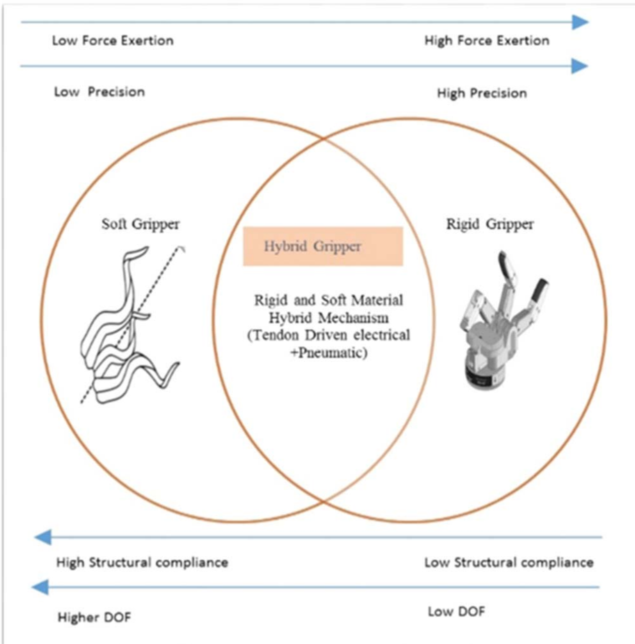

Figure 1. Position of the hybrid soft-rigid gripper in the design space, and

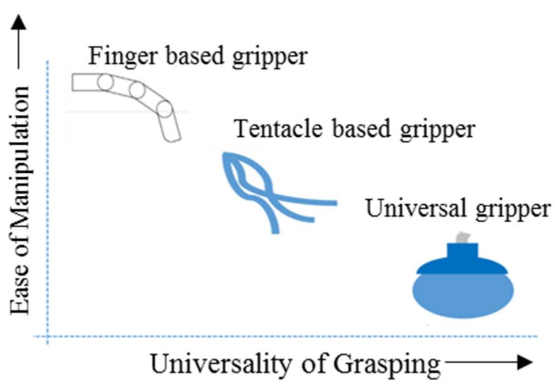

Figure 2. Ease of in-hand manipulation

Finger based grippers have superior ability in the in-hand manipulation, whereas soft universal gripper filled with granular materials are capable of grasping a wide range of products. On the other hand, a tentacle based gripper along with a rigid backbone has both the excellent grasping and medium for in-hand manipulation, as shown in Figure 2.

A. Proposed Finger Design

The primary responsibility must be kept in mind while designing the hybrid soft-rigid gripper in this study is that:

- The proposed hybrid soft-rigid gripper can adapt and grasp a variety of objects having different shape, size, weight, and materials.
- The fabrication process must be simple and easy. (Ease of fabrication)
- The interface of the developed hybrid gripper must demand into the existed hardware.
- The gripper may have the ability to perform the fingertip grasp and enveloping grasp.

A bioinspired approach has been considered by taking the inspiration from the human finger to develop the hybrid soft-rigid robotic gripper, which consists of rigid backbone and soft materials at the top connected by flexural hinges. The proposed hybrid gripper consists of three parts, which resemble the three phalanges of the human finger, such as MCP to PIP, PIP to DIP, and distal phalange. Each joint is connected with the help of a soft material flexible joint and actuated by a tendon driven mechanism driven by a single actuator. A conceptual design of the hybrid soft-rigid gripper with a rigid backbone and soft material top joined with flexural hinges is shown in Figure 3. The red line in the figure represents the tendon wire actuated by the electric motor. Flexural hinges of the hybrid soft-rigid gripper are represented in orange color. The entire gripper consists of three phalanges (L_1, L_2 *and* L_3) and the length of the flexural hinges are L_{H1} *and* L_{H2}.

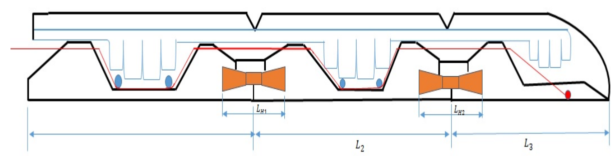

Figure 3. Conceptual design of a single finger

B. Mathematical modeling and Formulation of the objective function

The basis of the hybrid soft-rigid robot hand is to take advantage of soft and rigid materials. Due to the symmetric nature of the proposed hand which uses three identical finger, the present study focus on the analysis of a single finger in the 2D design space reasoning equivalent that of the actual hybrid soft-rigid robotic hand. A mathematical model for the single finger while grasping the object is presented, considering some assumptions presented below.

- The developed force on the object must be normal to the segment of the finger.
- The soft materials at the top of the proposed gripper act as rigid bodies.
- The contact positons of the object with the finger is present at the center of the width and length.
- The proposed robotic hand must have grasped the objects symmetrically within its three-finger.
- The developed tension due to tendon is constant at each flexural joints.
- The developed frictional force at the contact point between finger and object is neglected.

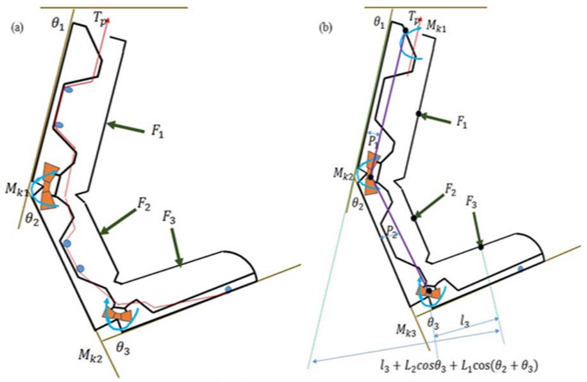

Figure 4. (a) Schematic layout of the single finger with contact forces and developed tensions, (b) Free body diagram of the proposed robotic finger concerning distal joint

Based on the assumptions mentioned earlier, a complicated model of grasping, the object can be a simplified model with three forces and a developed tension, as shown in Figure 4 (a).

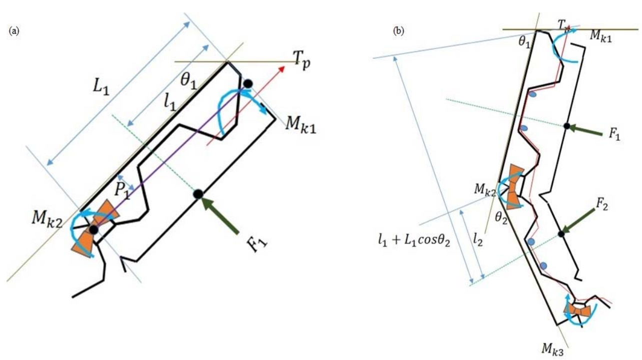

Figure 5. (a) FBD of a single robotic finger concerning proximal joint, (b) FBD of a single robotic finger concerning middle joint

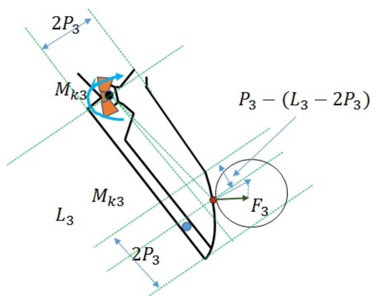

Figure 6. The schematic diagram for the fingertip grasp

When the finger is actuated by the tendon driven mechanism, three different types of forces developed within the systems such as tendon tension, spring return force, and contact force at the contact point between object and finger.

$$F_3 = \frac{M_{k3} - k_3\theta_3}{l_3} \tag{1}$$

$$F_2 = \frac{M_{k2} - M_{k1} - k_2\theta_2}{l_1 + L_1 cos\theta_2} \tag{2}$$

$$F_1 = \frac{M_{k3} - M_{k1} - M_{k2} - k_1\theta_1}{l_3 + L_2 cos\theta_3 + L_1 cos(\theta_2 + \theta_3} \tag{3}$$

From Eq. (1-3), we can formulate the objective functions f this study which is the sum of all three forces generated while grasping an object. The first objective is the maximization problem.

$$f_1 = F_1 + F_2 + F_3 \tag{4}$$

From Eq. (1-3), we can foormulate the second objective function of the proposed hybrid soft-rigid robotic hand and is represented by the magnitude of difference values among the contact forces. The proposed method is a minimization problem.

$$f_2 = \left(\overline{F} - F_1\right)^2 + \left(\overline{F} - F_2\right)^2 + \left(\overline{F} - F_3\right)^2 \tag{5}$$

$$\text{where } \overline{F} = \frac{F_1 + F_2 + F_3}{3}$$

The constraint equations of the systems are formulated by considering different criterion of the proposed systems. In this study, we use four constraint equations which must be satisfied while solving the multi-objective optimization problem.

1. The joint angle range are within the specified limit as follows:
   $\frac{\pi}{6} \le \theta_1 \le \frac{\pi}{4}; \frac{\pi}{4} \le \theta_2 \le \frac{\pi}{6}; 0 \le \theta_3 \le \frac{\pi}{2}$
2. The constraint at the fingertip position is obtained as $0 \le \frac{2P_3}{L_3} \le 1$
3. The distance between the third contact point (l_3) and the joint phalanx (L_3) must be higher than $(L_3 - 2P_3)$.
   $\in = P_3 - (L_3 - 2W_3)$
4. The width of the phalanges
   $\min(P_1, P_2, P_3) \ge \max(d_1, d_3, d_3)$

C. Optimization process using I-MOALO

The hunting behavior of antlion gave the inspiration to develop the Multi-Objective Ant Lion Optimizer (MOALO) (Mirjalili et al., 2017) [28]. The strongest Antlion, which has the maximum probability of catching prey, is known as the elite Antlion. MOALO algorithm is shown superior performance compared to other evolutionary algorithms due to its higher convergence rate with properties to avoids local optima because of its excellent exploration and higher exploitation that have a greater tendency to address the multi-objective problems with constraints equations. Previously, we developed an improved version of MOALO to find the optimal dimensions [29]. So, in this article, the improved mechanism of the algorithm is not elaborately explained. The fundamental differences are to use beta distribution and modified elitism approach in the improved version of the algorithm, which is explained elaborately in the article [29] and the schematic flow of the algorithm is shown in Figure 7. In this work, we used the I-MOALO to obtain the optimal design parameters of the proposed hybrid soft-rigid robotic hand.

Step 1: Initialization of the proposed algorithm

The first step of the algorithm is to deal with the initialization of different algorithm parameters. The position of the ants and the antlions obtained in the search space are the solution vectors that represent the design variables of the design optimization of the gripper.

Step 2: Initialization of ants and antlions position

The geometric and design parameters of the hybrid soft-rigid robotic hand are expressed as the position of the ants. It is compulsory to make the initialized value within the prespecified range that is stored in a matrix as Eq. (6).

$$M_{ant} = A_{i,j} = \begin{bmatrix} A_{1,1} & A_{1,2} & \cdots & A_{1,d} \\ A_{2,1} & A_{2,2} & \cdots & A_{2,d} \\ \vdots & \vdots & \ddots & \vdots \\ A_{N,1} & A_{N,2} & \cdots & A_{N,d} \end{bmatrix}$$
$$i \in N \; (total\ numbers\ of\ ants), \quad j \in d \; (\text{dim}ension\, of\ the\ search\ space) \tag{6}$$

In the above Eq. (8), the term $A_{i,j}$ signifies the total ant populations in the predefined search space, and N denotes the number of ants of the systems. Similarly, the antlions dimension is represented in a matrix denoted by $M_{antlion}$ Eq. (7).

$$M_{antlion} = A_{i,j} = \begin{bmatrix} AL_{1,1} & AL_{1,2} & \cdots & AL_{1,d} \\ AL_{2,1} & AL_{2,2} & \cdots & AL_{2,d} \\ \vdots & \vdots & \ddots & \vdots \\ AL_{N,1} & AL_{N,2} & \cdots & AL_{N,d} \end{bmatrix} \tag{7}$$

The position of each vector is a solution to the proposed hybrid soft-rigid hand. The range of beta distribution for this study is within [0,1]. The positions of ant and antlions are obtained using Eq. (8).

$$A_{i,j} = A^{L}_{i,j} + betarnd(A^{U}_{i,j} - A^{L}_{i,j}) \tag{8}$$

where, lower limits are represented as $A^{L}_{i,j}$, and the upper limits of the system are denoted by $A^{U}_{i,j}$.

Step 3: Ants random walks

The stochastic nature of the ant's movement for the food search can be expressed as the random walk and represented as Eq. (9).

$$\bar{X}_i(p) = \left[o, \sum_{j=1}^{1}(2y_j - 1), \sum_{j=1}^{2}(2y_j - 1), \cdots, \sum_{j=1}^{N_w}(2y_j - 1) \right] \tag{9}$$

The developed function is normalized to restrict the positions of the ants within the predefined area can be represented in Eq. (10).

$$\bar{X}_i(p)\Big|_{norm} = \frac{(\bar{X}_i(p) - a_i(p)) \times (d_i(p) - c_i(p))}{b_i(p) - a_i(p)} \tag{10}$$

where $a_i(p)$ represents the minimum and $b_i(p)$ represents maximum values of the i[th] variable of the normalized function $\bar{X}_i(p)\Big|_{norm}$.

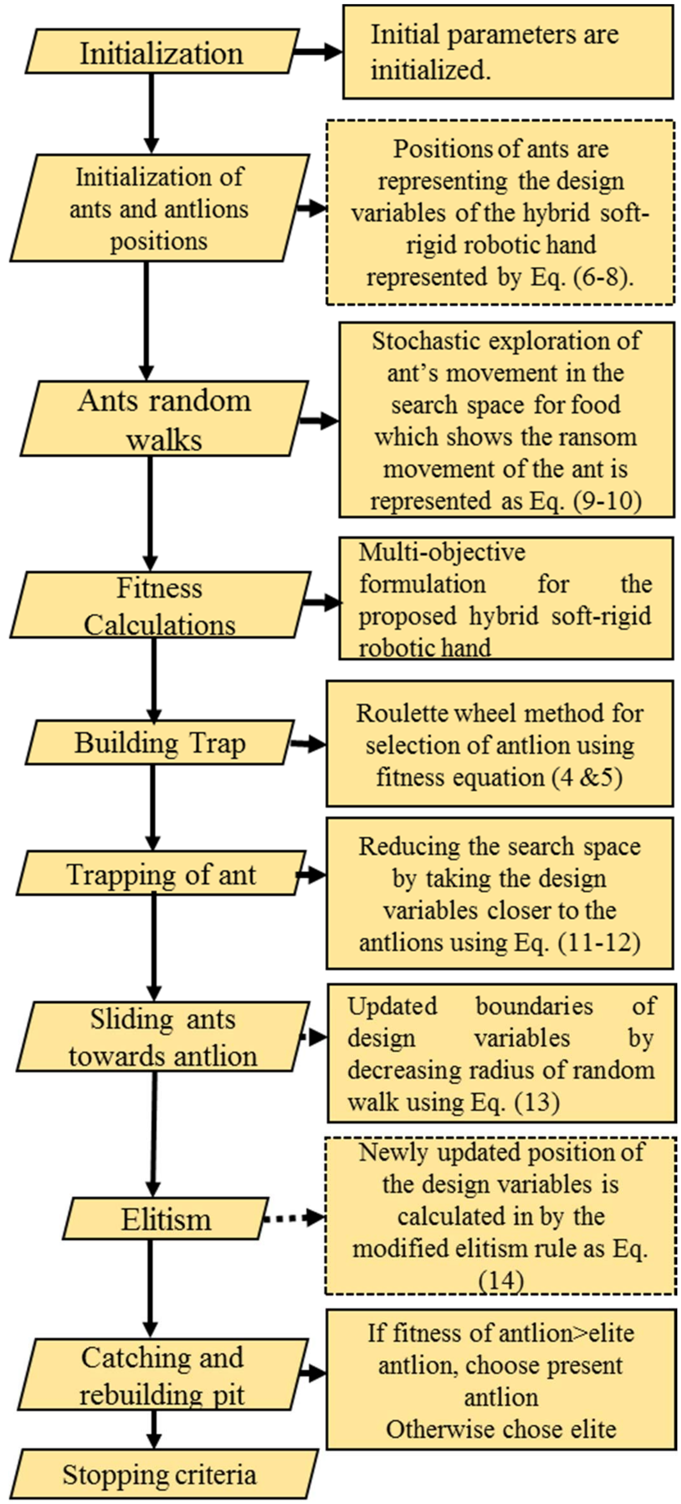

Figure 7. Improved Antlion algorithm

Step 4: Fitness Calculations

In this work, we derived the optimal dimensional analysis problem as a multi-objective optimization problem with two conflicting objective functions and five constraints equations and solved for the dimension of the hybrid soft-rigid robotic hand that used to fabricate the prototype.

Step 5: Building Trap
Roulette wheel method is used for the selection of the elite antlion using their fitness value.
Step 6: Trapping of ants
It is necessary to reduce the search space of the antlions by considering the positions of the design variables closer to the antlions, and the mathematical model is expressed in Eq. (11 & 12).

$$c_i(p) = antlion_j(p) + c_i(p) \tag{11}$$

$$d_i(p) = antlion_j(p) + d_i(p) \tag{12}$$

where $c_i(p)\,\&\,d_i(p)$ are the smallest and largest of all variables at i^th repetition in the dimensional predefined search space.

Step 7: Sliding ants towards antlion
The range of the updated search space is reduced by decreasing the ant's random walk radius and is represented in mathematical form as Eq. (13).

$$c_i(p) = \frac{c_i(p)}{I_{adaptive}}, d_i(p) = \frac{d_i(p)}{I_{adaptive}} \tag{13}$$

Where $c_i(p)$ *and* $d_i(p)$ is the smallest limit of i^th variable and highest bounds of the i^th variable, respectively, whereas $I_{adaptive} = 100^w * p / N_i$ represents an adaptive factor of the algorithm.
Step 8: Elitism
In this section of the proposed algorithm deals with the modification of the elitism phase of the original MOALO that is represented as Eq. (14).

$$ant_i(p) = \alpha_A R_A + \alpha_E R_E \tag{14}$$

where α_A and α_E are the carefully selected coefficient weights most suitable for the proposed systems.
Step 9: Catching prey and re-building pit
This phase of the proposed algorithm is mathematically formulated as Eq. (15), which find the fittest or healthiest antlion iteratively.

$$antlion_j(p) = ant_i(p)$$
$$if \;\; f(ant_i(p)) > f(antlion_j(p)) \tag{15}$$

Step 10: Stopping condition of the algorithm

When current results satisfy the requirement of the proposed system leads to the optimal solution of the proposed schemes. The employment procedure to find the optimal dimensions of the proposed hybrid soft-rigid robotic gripper is shown in Figure 8.

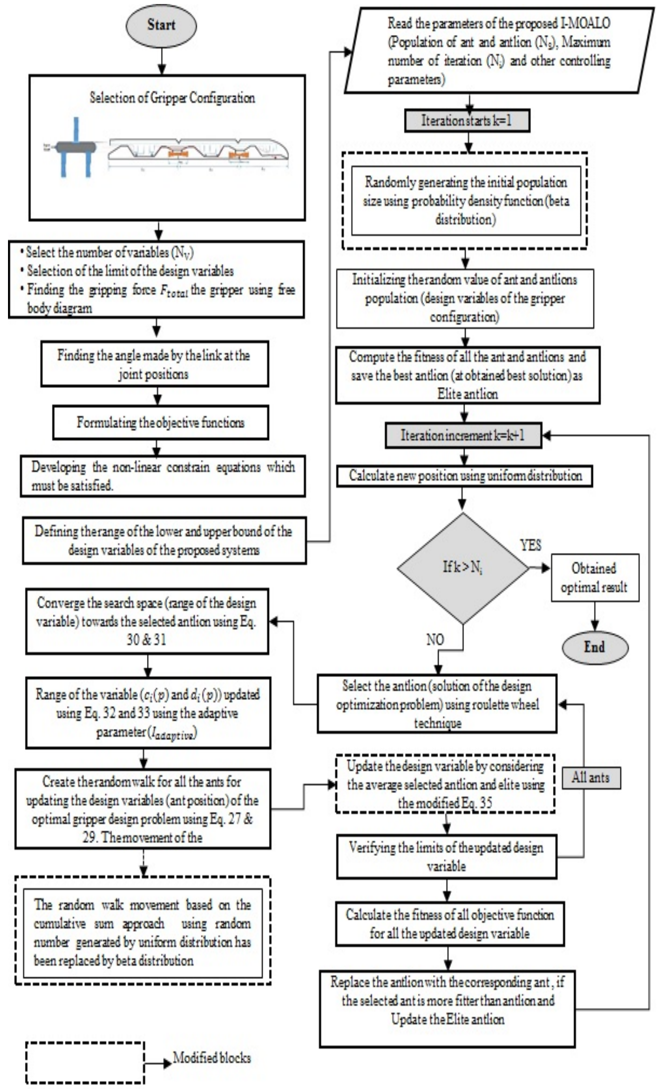

Figure 8. Implementation procedure to find out the optimal dimensions of the hybrid soft-rigid hand

IV. RESULTS AND DISCUSSION

To validate the proposed methodology to obtain the optimal geometric parameters of a hybrid soft-rigid robotic hand, a simulation study is conducted using the I-MOALO algorithm in MATLAB R2015a. The algorithm parameters for this study are presented in Table 1. A clear explanation regarding the selection of the tuning parameters can be found in the article [29], which is beyond the scope of this article.

Table 1. Tuning parameters of I-MOALO

Algorithm	Pop. Size	No. of iterations	Max. Size of Archive
I-MOALO	400	400	400

The proposed multi-objective problem is solved using the algorithm, and the obtained result in terms of Pareto font is present in Figure 9. The designer's sole responsibility to select the most appropriate design criteria according to their application from the obtained Pareto font. Here, we considered three points, as shown in Figure 9, by considering a point at the extreme right (Pont C), one point at center (Point B), and other at the extreme left (Point A). All three points of the Pareto fonts are selected, keeping in attention that considers all the area while obtaining the optimal geometric parameters of the proposed systems. All the geometric design parameters are in mm, which can be obtained from the selected points of the Pareto fonts. The limits of the predefined design variables are presented in Table 2.

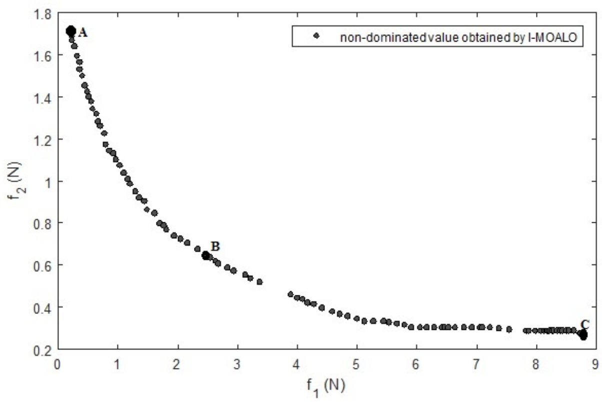

Figure 9. Obtained Non-dominated solutions using I-MOALO

Table 2. Preset limits of the design variable

Design parameters (mm)	L_1	L_2	L_3	d_1	d_2	d_3	$2P_1$	$2P_2$	$2P_3$
Lower Limit (mm)	35	20	10	6	6	6	12	12	12
Upper Limit (mm)	55	50	30	20	20	20	22	22	22

The main responsibility in multi-objective optimization problem is to select the most suitable Pareto solution and the trade-off solution from the obtained result is selected on the designer choice. Area of application of the robotic hand plays a crucial role while the selection of the pareto fonts. Small objects grasping required the précised gripper which have the tendency to grasp the objects with higher accuracy and with minimum force. A fuzzy membership function is employed to find the optimal points among all the solutions for this study.

$$f_{avg} = \frac{f_1+f_2}{2} \tag{16}$$

where, f_{avg} is the average fuzzy membership function, $f_1 = \frac{F_{1max}-F_1}{F_{1max}-F_{1\min}}$; $f_2 = \frac{F_{2max}-F_2}{F_{2max}-F_{2\min}}$;

Table 3. Obtained optimal design variable

Point	$f_1(x)$	$f_2(x)$	L_1	L_2	L_3	d_1	d_2	d_3	$2P_1$	$2P_2$	$2P_3$
A	0.195	1.714	55.2	34.1	25.7	15.4	7.9	16.9	17.6	17.1	18.4
B	2.944	0.569	53.8	33.2	25.0	15.5	7.7	16.8	17.2	16.8	17.9
C	6.788	0.268	52.9	35.4	24.2	15.3	7.1	15.8	17.5	17.2	18.0

In an optimal structural analysis of the systems, a sensitivity study must be integrated with the systems to find the most accurate results. After picking the best design parameters, the final step of the design optimization problem is to investigate the design sensitivity to the changes in the design variables, which calculates the rate of change of fitness function while giving tolerances to the obtained design parameters assuming that the objective function to be differentiable. To achieve an accurate and efficient distribution of tolerances on the link length of the hybrid soft-rigid robotic gripper, the designer must be conducted a sensitivity analysis. A sensitivity analysis permits the designer to detect the utmost critical link of the proposed hybrid soft-rigid robotic hand and able to assign optimal tolerance to it. The optimal solution (y*) is selected from point B, as illustrated in Table 3, and sensitivity analysis of the hybrid soft-rigid gripper is demonstrated using the following Eq. (17).

Considering tolerances on link lengths, the actual lengths of the links deviate from the nominal: $y_{i\,act} = y_{i\,nom+\Delta y_i}$.

$$\Delta f_1 = \nabla y^T . \nabla f_1(y^*) + \frac{1}{2} \Delta y^T . H_1(y^*) . \Delta y \tag{17}$$

where $\Delta y = (\Delta L_1, \Delta L_2, \Delta L_3, \Delta d_1, \Delta d_2, \Delta d_3, \Delta 2P_1, \Delta 2P_2, \Delta 2P_3)$

$\Delta f_1 = first\ partail\ derivative\ and\ H_1\ hessian\ matrix$

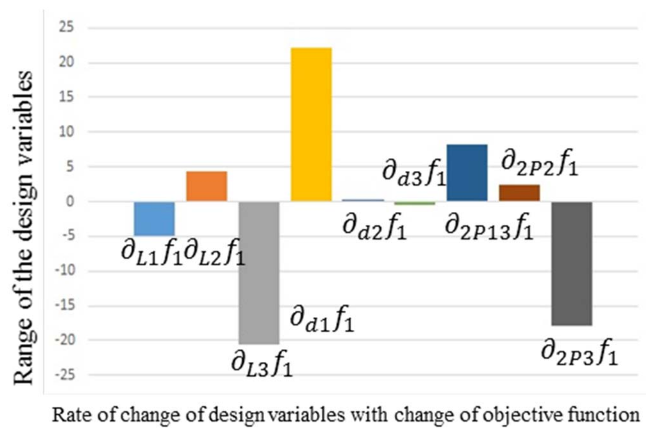

Figure 10. Sensitivity analysis for the first objective function

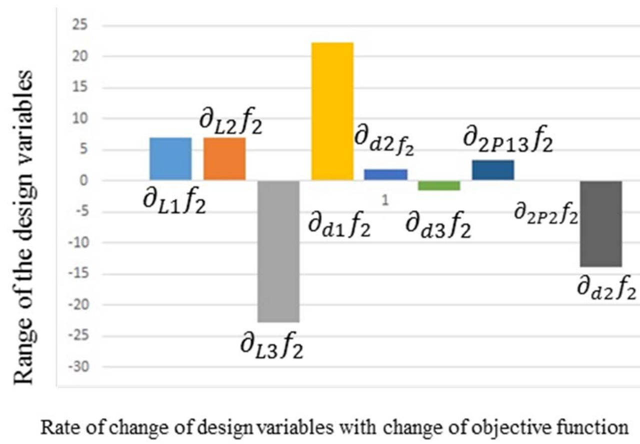

Figure 11. Sensitivity analysis for the second objective function

Figure 10 and 11, illustrates the results obtained from the design sensitivity analysis which shows that parameters L3, d1 and 2P3 varies significantly compared to the other parameters, hence while developing the prototype, it is necessary to give tolerances to these parameters. All the different color in Figure 10 and 11 represents the different design parameters of the proposed systems.

Table 4. Comparison with other algorithms

	$f_1(x)$	$f_2(x)$	L_1	L_2	L_3	d_1	d_2	d_3	$2P_1$	$2P_2$	$2P_3$
NSGA-II	5.2	2.4	50.2	30.5	26.2	17.4	8.9	18.9	19.6	16.6	17.8
MOALO	3.8	1.2	54.6	34.2	26	15.8	8.3	17	17.5	17.9	18
I-MOALO	2.94	0.56	53.8	33.2	25	15.5	7.7	16.8	17.2	16.8	17.9

Table 5. Computation time comparison

Algorithms	Time (S)
NSGA-II	179.45
MOALO	143.67
I-MOALO	120.5

In Table 4, a comparative study is presented with the other algorithms which shows that proposed algorithm performs better and Table 5 represent the computation time of the algorithms. A preliminary robotic gripper is fabricated considering the obtained dimensions as shown in Figure 12.

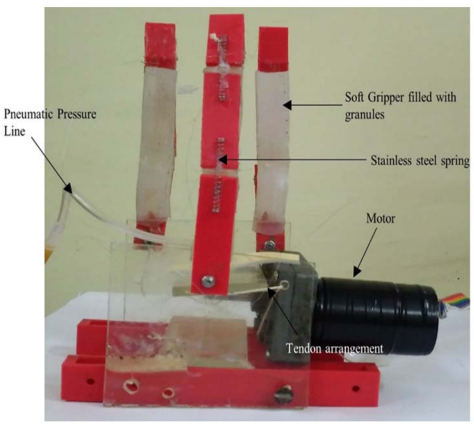

Figure 12. Fabricated preliminary prototype considering the obtained dimensions

V. CONCLUSION

This article presents a new and efficient approach for finding the optimal design conditions for a hybrid soft-rigid robotic gripper. The optimal design optimization problem of the hybrid soft-rigid robot gripper is formulated as a multi-objective optimization problem with two objective functions. The optimization problem is solved effectively by an improved multi-objective antlion optimizer (I-MOALO) method with beta distribution to generate an initial random number and compared with other algorithms to verify its effectiveness. Finally, a design sensitivity analysis has been investigated to find the effect of change in the design variable towards the objective functions of the proposed hybrid soft-rigid robotic hand. In future, we extended this study to investigate for the bio-inspired optimization process, topology optimization, and control methodology to handle the hybrid soft-rigid robotic hand.

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