

Multi-Objective Design and Analysis of Robot Gripper Configurations Using an Evolutionary-Classical Approach

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ABSTRACT

This paper is concerned with the determination of optimum forces extracted by robot grippers on the surface of a grasped rigid object – a matter which is crucial to guarantee the stability of the grip without causing defect or damage to the grasped object. A multi-criteria optimization of robot gripper design problem is solved with two different configurations involving two conflicting objectives and a number of constraints. The objectives involve minimization of the difference between maximum and minimum gripping forces and simultaneous minimization of the transmission ratio between the applied gripper actuator force and the force experienced at the gripping ends. Two different configurations of the robot gripper are designed by a state-of-the-art algorithm (NSGA-II) and the obtained results are compared with a previous study. Due to presence of geometric constraints, the resulting optimization problem is highly non-linear and multi-modal. For both gripper configurations, the proposed methodology outperforms the results of the previous study. The Pareto-optimal solutions are thoroughly investigated to establish some meaningful relationships between the objective functions and variable values. In addition, it is observed that one of the gripper configurations completely outperforms the other one from the point of view of both objectives, thereby establishing a complete bias towards the use of one of the configurations in practice.

Categories and Subject Descriptors

I.2.8 [Computing Methodologies]: Problem Solving, Control Methods, and Search

General Terms

Algorithms

Keywords

Robot gripper design, Multi-criteria optimization, Pareto-optimal front, Hybrid evolutionary-classical methodology.

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1. INTRODUCTION

Evolutionary multi-objective optimization (EMO) is getting increasing attention to solve real-world problems among the scientific and engineering community. This is because, real-world problems are often multi-objective in nature and consist of non-linear, non-convex, and discontinuous objective functions and constraints. In most of the situations, conventional optimization techniques cannot handle such complexities well and are largely unsuccessful to produce a satisfactory solution. Evolutionary algorithms are flexible, less-structured and are found to provide an alternative and effective way to tackle these difficult optimization problems with the fast increase in computing power.

The role of a robot gripper mechanism is significant in today's industrial systems, as it is the interacting device between environment and the object to be picked and placed to perform grasping and manipulation tasks. With the evolution of automation in industries, grasping become an important topic in robotics research community. The motivation of growing research in robot gripper design came from human hand [11], [9]. Robot grippers are attached in the wrist of the robot to grasp and manipulate an object. The basic purpose of robot gripper is to hold, grip, handle and release an object in the same way a human hand can do [3]. The driving mechanism for a gripper can be hydraulic, electrical and pneumatic.

There are many previous studies in literature on robot gripper design. Cutkosky [5] carried out a study on the choice, model and design of grasp and developed an expert system to resolve grasping issues. Osyczka [10] proposed a multi-objective optimization based robot gripper design and solved the gripping problem with different configurations. Ceccarelli et al. [2], [4] performed dimensional synthesis of gripper mechanisms using Cartesian coordinates. The formulation was based on practical design requirements and the aim was to derive an analytical formulation using an index of performance (Grasping Index) to describe both kinematic and static characteristics. Cabrera et al. [1] developed a strategy using evolutionary algorithm for optimal synthesis of a two-hand multi-objective constrained planar mechanism. They validated the results by evaluating the mechanism with some points on the Pareto-optimal front and showed satisfactory result. Another study [8] proposed an optimum design of two-finger robot gripper mechanism using multi-objective formulation, considering the efficiency, dimension, acceleration and velocity of the grasping mechanisms and reported a case study by using 8R2P linkage. A recent study [12] proposed kinematic design of serial manip-

ulators. The method provides uniform manipulability over the workspace and genetic algorithms are used to solve the resulting linear problem.

In this paper, we borrow two robot gripper configurations from Osyczka [10] and perform a bi-objective study to understand the trade-off between chosen objectives. In the following sections, first we describe the gripper mechanism configurations and present the corresponding multi-objective optimization problems. The optimization problems are then solved using the Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) [6]. Evaluation of every solution requires another single-objective maximization problem which we solve using a classical golden section search method. The NSGA-II obtained fronts are compared with an earlier study and superiority of obtained results is demonstrated. Thereafter, using the obtained trade-off solutions, we perform an *innovation* study [7] to unveil important design principles related to the gripper dimensions. Finally, we compare optimal solutions of both the gripper problems and conclude the superiority of one over the other. The paper ends with the conclusions of this study.

2. GRIPPER-I CONFIGURATION DESIGN

The motivation of the present work is to design the structure of a robot gripper (shown in Figure 2) optimally. The original problem was formulated elsewhere [10]. The goal of the optimization problem is to find the dimensions of elements of the grippers and optimize a couple of objective functions simultaneously by satisfying the geometric and force constraints. The vector of seven design variables are $\mathbf{x} = (a, b, c, e, f, l, \delta)^T$, where a, b, c, e, f, l are dimensions (link lengths) of the gripper and δ is the angle between elements b and c . The structure of geometrical dependencies of the mechanism can be described as follows and are also illustrated in Figure 2:

$$\begin{aligned} g &= \sqrt{(l-z)^2 + e^2}, \\ b^2 &= a^2 + g^2 - 2.a.g.\cos(\alpha - \phi), \\ \alpha &= \arccos\left(\frac{a^2 + g^2 - b^2}{2.a.g.}\right) + \phi, \\ a^2 &= b^2 + g^2 - 2.b.g.\cos(\beta + \phi), \\ \beta &= \arccos\left(\frac{b^2 + g^2 - a^2}{2.b.g.}\right) - \phi, \\ \phi &= \arctan\left(\frac{e}{l-z}\right). \end{aligned}$$

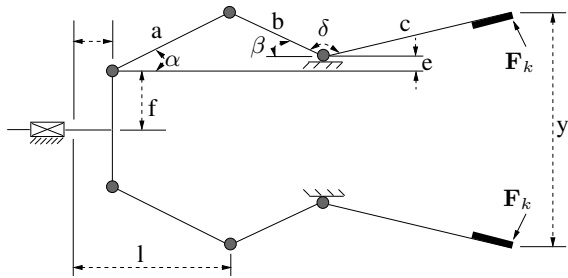


Figure 1: A sketch of robot Gripper-I.

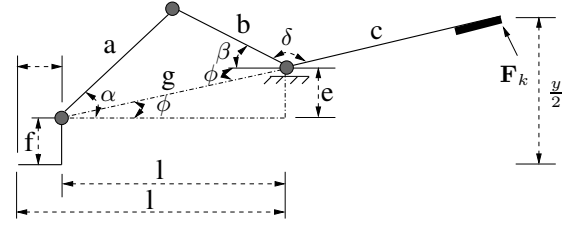


Figure 2: Geometrical dependencies of the Gripper-I mechanism.

The free body diagram for the force distribution is shown in Figure 3. From the figure, we can write the following:

$$\begin{aligned} R.b.\sin(\alpha + \beta) &= F_k.c, \\ R &= \frac{P}{2.\cos\alpha}, \\ F_k &= \frac{P.b.\sin(\alpha + \beta)}{2.c.\cos\alpha}, \end{aligned}$$

where R is the reaction force on link a and P is the actuating force applied from the left side to operate the gripper.

From the above correlations the objective functions can be formulated as follows:

1. The first objective function can be written as the difference between the maximum and minimum gripping forces for the assumed range of gripper ends displacement:

$$f_1(\mathbf{x}) = \max_z F_k(\mathbf{x}, z) - \min_z F_k(\mathbf{x}, z). \quad (1)$$

The minimization of this objective ensures that there is not much variation in the gripping force during the entire range of operation of the gripper.

2. The second objective function is the force transmission ratio, the ratio between the applied actuating force P and the resulting minimum gripping force at the tip of link c :

$$f_2(\mathbf{x}) = \frac{P}{\min_z F_k(\mathbf{x}, z)}. \quad (2)$$

The minimization of this objective will ensure that the gripping force experienced at the tip of link c has the largest possible value.

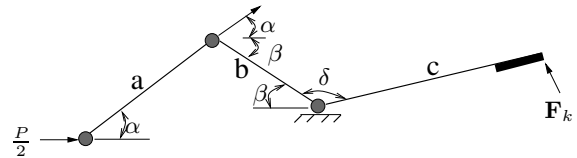


Figure 3: Force distribution of mechanism of the Gripper-I.

In the aforesaid multi-objective optimization problem, both objective functions depend on the vector of decision variables and on the displacement z . Thus for a given solution vector \mathbf{x} , the values of the conflicting objective functions

$f_1(\mathbf{x})$ and $f_2(\mathbf{x})$ requires to find the maximum and minimum value of gripping force $F_k(\mathbf{x}, z)$ for different possible values of z . The parameter z is the displacement parameter which takes a value from zero to Z_{\max} . Taking a small finite increment in z , recording the corresponding F_k value for each z , and then locating the maximum and minimum values of F_k is a computationally time-consuming proposition. Here, we employ the well-known golden section search algorithm for locating minimum and maximum F_k . It is important to note that these extreme values may take place at one of the two boundaries (either $z = 0$ or $z = Z_{\max}$) and the golden section search is capable of locating them. The only drawback of the golden section search is that it can locate the minimum of a unimodal function accurately, but for multimodal problems the algorithm is not guaranteed to find an optimum. Fortunately, for this problem, we have checked the nature of F_k variation for a number of different solution vectors (\mathbf{x}) and every time a unique maximum in the specified range of z is observed. A typical variation is shown in Figure 4. Although there is usually a single maximum

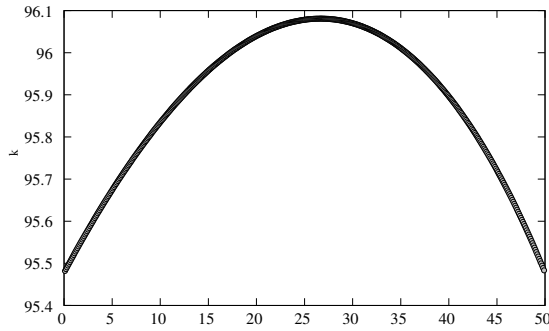


Figure 4: Variation of force F_k with the displacement z for a typical \mathbf{x} for Gripper-I.

point, one of two extremes have been found to correspond to the minimum F_k . Thus, for locating the minimum F_k , we simply check the two extreme values of z and use the one having the smaller value of F_k .

The gripper problem also has a number of non-linear constraints:

1. The dimension between ends of gripper for maximum displacement of actuator should be less than minimal dimension of the gripping object:

$$g_1(\mathbf{x}) = Y_{\min} - y(\mathbf{x}, Z_{\max}) \geq 0,$$

where $y(\mathbf{x}, z) = 2.[e + f + c. \sin(\beta + \delta)]$ is the displacement of gripper ends and Y_{\min} is the minimal dimension of the gripping object. The parameter Z_{\max} is the maximal displacement of the gripper actuator.

2. The distance between ends of gripper corresponding to Z_{\max} should be greater than zero:

$$g_2(\mathbf{x}) = y(\mathbf{x}, Z_{\max}) \geq 0.$$

3. The distance between the gripping ends corresponding to no displacement of actuator (static condition) should be greater than the maximum dimension of gripping object:

$$g_3(\mathbf{x}) = y(\mathbf{x}, 0) - Y_{\max} \geq 0,$$

where Y_{\max} is the maximal dimension of the gripping object.

4. Maximal range of the gripper ends displacement should be greater than or equal to the distance between the gripping ends corresponding to no displacement of actuator (static condition):

$$g_4(\mathbf{x}) = Y_G - y(\mathbf{x}, 0) \geq 0, \quad (3)$$

where Y_G is the maximal range of the gripper ends displacement.

5. Geometrical properties are preserved by following two constraints:

$$g_5(\mathbf{x}) = (a + b)^2 - l^2 - e^2 \geq 0.$$

$$g_6(\mathbf{x}) = (l - Z_{\max})^2 + (a - e)^2 - b^2 \geq 0.$$

The graphical illustration of constraint $g_5(\mathbf{x})$ and $g_6(\mathbf{x})$ is shown in Figure 5.

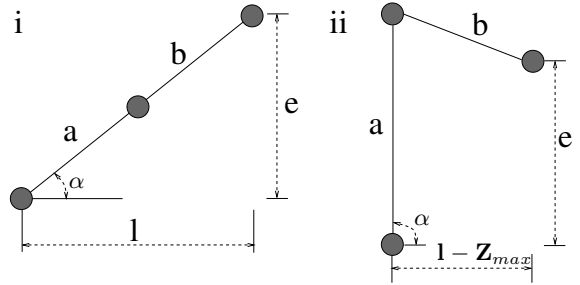


Figure 5: Geometric illustration of constraints i) $g_5(\mathbf{x})$ ii) $g_6(\mathbf{x})$ for Gripper-I.

6. From the geometry of the gripper the following constraint can be derived:

$$g_7(\mathbf{x}) = l - Z_{\max} \geq 0. \quad (4)$$

7. The minimum gripping force should be greater than or equal to chosen limiting gripping force:

$$g_8(\mathbf{x}) = \min_z F_k(\mathbf{x}, z) - FG \geq 0, \quad (5)$$

where FG is the assumed minimal gripping force.

2.1 NSGA-II-cum-Golden-Section Search and Results

We employ the constraint handling strategy of NSGA-II to take care of all of the above constraints. The gripper dimensions can be such that for some displacement value z , the gripper configuration is no more a mechanism or there is a locking in the mechanism. We first check for such a scenario by considering a fixed increment of z by 0.1 mm. If such a scenario happens, we penalize the solution by a large amount to discourage its presence in the NSGA-II population. Otherwise, as discussed above, for every population member, the golden section search approach is employed to compute maximum F_k value and check the extremes of z to compute the minimum value of F_k .

The other fixed parameter values for the problem and NSGA-II parameters are given in the following:

1. The variable bounds of all the link lengths and angle are as follows: $10 \leq a \leq 250$, $10 \leq b \leq 250$, $100 \leq c \leq 300$, $0 \leq e \leq 50$, $10 \leq f \leq 250$, $100 \leq l \leq 300$, $1.0 \leq \delta \leq 3.14$.
2. The geometric parameters are: $Y_{\min} = 50 \text{ mm}$, $Y_{\max} = 100 \text{ mm}$, $Y_G = 150 \text{ mm}$, $Z_{\max} = 50 \text{ mm}$, $P = 100 \text{ N}$ and $FG = 50 \text{ N}$.
3. NSGA-II parameters are as follows: population size = 200, probability of SBX recombination = 0.9, probability of polynomial mutation = 0.1, distribution index for real-variable SBX crossover = 20, and distribution index for real-variable polynomial mutation = 100.

Figure 6 shows the obtained non-dominated front by NSGA-II-cum-golden-section search procedure. To compare our results, we also plot the results reported in another study [10] (we term these results as ‘Original’ here). After 1,000 generations of NSGA-II, the obtained trade-off front completely outperforms that reported in the original study. However, as we keep running our procedure, a betterment in the trade-off frontier is noticed. We then ran our procedure for a large number of generations and the resulting front is shown to be substantially better. This front is also shown in the figure. An increase in generations or use of different initial populations did not seem to change the front in any significant manner.

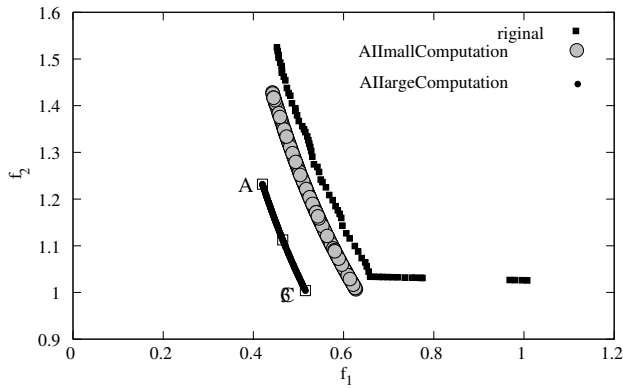


Figure 6: Trade-off solutions obtained using NSGA-II run for small and large number of generations for Gripper-I. Solutions are compared with the original study [10].

To investigate the changes in configurations of the gripper from one extreme trade-off solution to the other, we take two extreme solutions (A and C) and one intermediate solution (B) and show a diagram for each in Figure 7.

2.2 Innovization Study on Gripper-I

Interestingly and surprisingly, the grippers change in only one of the dimensions, whereas the remaining six design variables have an identical value. To investigate how one trade-off solutions vary from the other, we now analyze the values of seven design variables as a function of one of the objectives (force transmission ratio). Figures 8 to 14 show these plots. It is clear that dimensions a and b are fixed at their allowable upper limit value, dimensions e and l are fixed at their allowable lower limit value, and dimension f and the

angle δ are set to an intermediate value (37 mm and 98.6 degrees, respectively). The only way one optimal configuration changes to another optimal configuration by making a trade-off between two objectives is that the dimension c (gripper length) changes monotonically (Figure 14) with the force transmission ratio (the second objective). For a higher force transmission ratio, the dimension c must be large and vice versa. This can be explained from the fact that for a large link-length c , the force experienced at the tip will be small, thereby making a large value of f_2 . Thus, if a better grip is desired, it is better to have a smaller link-length c and keep all the other variables to their prescribed values as discussed above.

In some sense, this *innovized* design principles suggest that if a designer wants to guarantee an optimal configuration the dimensions a , b , e , f and l , and angle δ must be set at some specific values, but the dimension c (gripper length) can be varied to suit the required trade-off in the two chosen objectives. When we fit the c -variation with the second objective, we observe the following linear empirical relationship:

$$c = 243.6f_2. \quad (6)$$

Such design principles are useful to not only design an optimal configuration, but also to get valuable insight about the properties of possible optimal solutions under a multi-objective scenario.

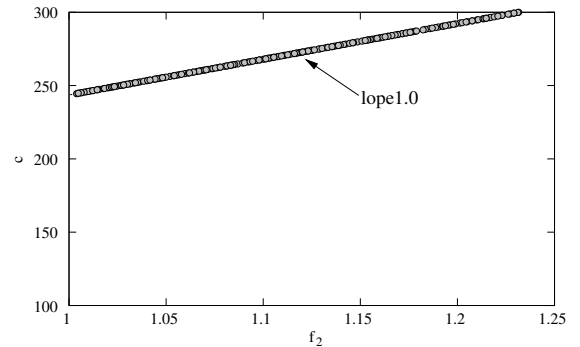


Figure 14: Variation of link length c with force transmission ratio for Gripper-I.

Before we leave this problem, we would like to discuss an important aspect of the innovization study. Innovization task is performed on a set of Pareto-optimal points to decipher salient principles which are common to the optimal points. Such principles are then expected to provide valuable knowledge about properties common to optimal solutions and that do not exist in non-optimal solutions. However, if such a task is performed on a set of non-dominated set of solutions away from the Pareto-optimal set, there may exist some other relationships common to them, but they may be different from the *innovized* principles common to Pareto-optimal solutions. For this problem, we have two fronts, as shown in Figure 6, one obtained with a reduced computational effort and one that was obtained with a large number function evaluations. When we perform an innovization task on the front obtained after 1,000 generations, a different set of principles emerged. Table 1 tabulates the differences in innovization principles of two sets of solutions.

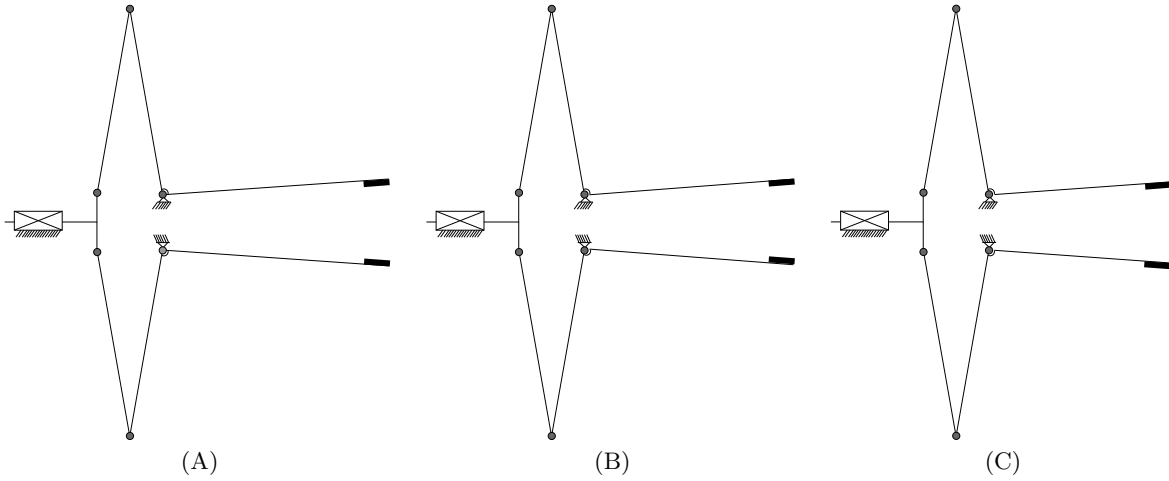


Figure 7: Three configurations taken from the NSGA-II front for Gripper-I.

Although both sets make all but one of the variables constant across the front, the constant values are somewhat different from each other. The trade-off points in both sets differ only in the link-length c . This study reveals the fact that by keeping all but c variable fixed may achieve a trade-off among the objectives, but there exist one set of fixed values (shown in the first row of the table) that makes the front close to the Pareto-optimal and is of interest to designers.

It can be observed from the table that while the larger computational results make four of the seven variables to lie on their allowable bounds (lower or upper), the smaller computational results make only one of the variables lie on its upper bound. Due to the highly non-linear and trigonometric terms in the constraints, it took a large number of generations before the near-optimal solutions could be found.

3. GRIPPER-II CONFIGURATION DESIGN

An overall sketch of the Gripper-II is shown in Figure 15 and was discussed in [10]. This configuration is somewhat

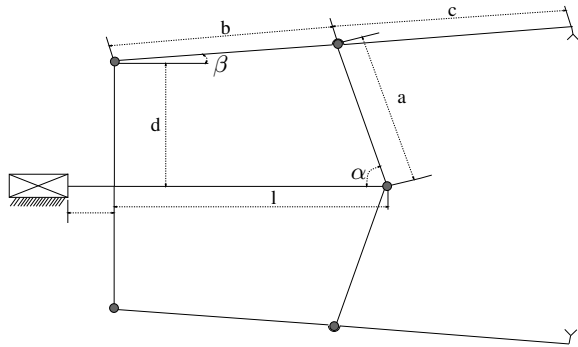


Figure 15: A sketch of robot Gripper-II.

simpler than Gripper-I. The design variable vector is $\mathbf{x} = (a, b, c, d, l)^T$, where the elements of this vector are five link-lengths of the gripper. By using geometrical relations,

we can write the following:

$$\begin{aligned}
 g &= \sqrt{(l+z)^2 + d^2}, \\
 \alpha &= \arccos\left(\frac{a^2 + g^2 - b^2}{2.a.g}\right) + \phi, \\
 a^2 &= b^2 + g^2 - 2.b.g.\cos(\beta + \phi), \\
 \beta &= \arccos\left(\frac{b^2 + g^2 - a^2}{2.b.g}\right) - \phi, \\
 \phi &= \arctan\left(\frac{d}{l+z}\right).
 \end{aligned}$$

The distribution of the forces is presented in Figure 16. Based on the figure, we can write the following:

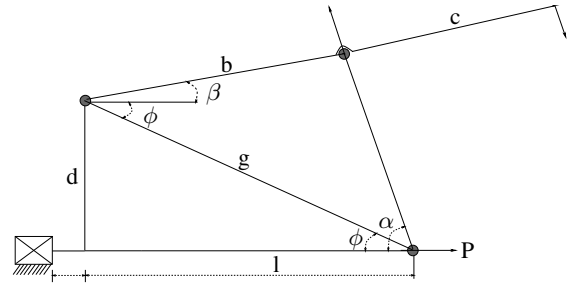


Figure 16: Distribution of forces on Gripper-II.

$$\begin{aligned}
 R.b.\sin(\alpha + \beta) &= F.(b + c), \\
 R &= \frac{P}{2.\cos(\alpha)}, \\
 F_k &= \frac{P.b.\sin(\alpha + \beta)}{2.(b + c).\cos\alpha}.
 \end{aligned}$$

Two objectives used in this study are identical to that in Gripper-I. However, the constraints are somewhat different. The first four constraints are exactly the same as discussed in Gripper-I. The other constraints are as follows:

$$\begin{aligned}
 g_5(\mathbf{x}) &= c - Y_{\max} - a \geq 0, \\
 g_6(\mathbf{x}) &= (a + b)^2 - d^2 - (l + z)^2 \geq 0, \\
 g_7(\mathbf{x}) &= \alpha \leq \frac{\pi}{2},
 \end{aligned}$$

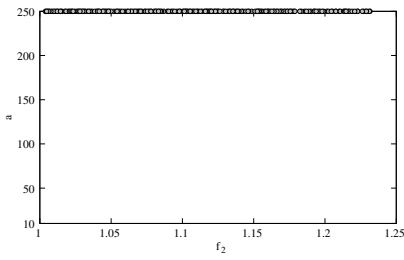


Figure 8: Variation of link length a with force transformation ratio for Gripper-I.

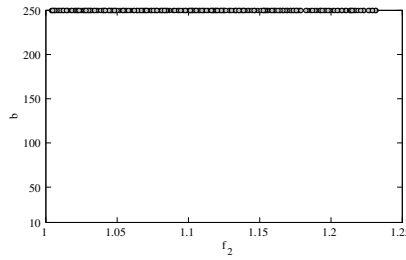


Figure 9: Variation of link length b with force transformation ratio for Gripper-I.

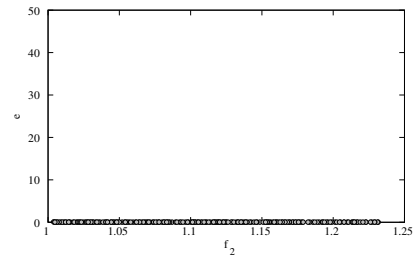


Figure 10: Variation of link length e with force transformation ratio for Gripper-I.

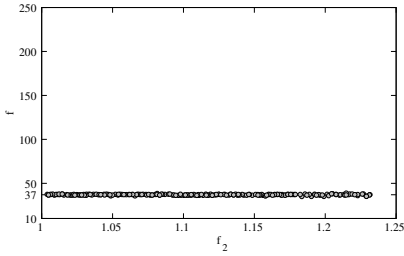


Figure 11: Variation of link length f with force transformation ratio for Gripper-I.

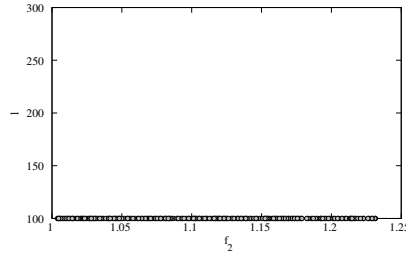


Figure 12: Variation of link length l with force transformation ratio for Gripper-I.

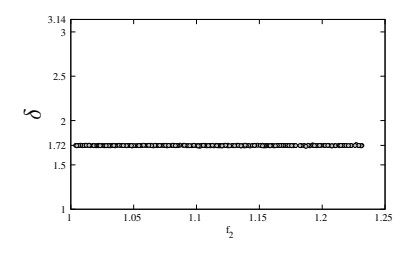


Figure 13: Variation of angle δ with force transformation ratio for Gripper-I.

Table 1: Comparison of *innovized* principles of two sets of trade-off solutions for Gripper-I.

	a	b	c	e	f	l	δ
	[10,250]	[10,250]	[100,300]	[0,50]	[10,250]	[100,300]	[1.00,3.14]
Large computations	250	250	$243.6f_2$	0	37	100	98.6°
Small computations	250	233	$210.3f_2$	14	15	180	106.0°

where, $y(\mathbf{x}, z) = 2(d + (b + c)) \sin(\beta)$ is the displacement of gripper ends, Y_{\min} is the minimal dimension of the gripping object, Y_{\max} is the maximal dimension of the gripping object, Y_G is the maximal range of the gripper ends displacement, and Z_{\max} is the maximal displacement of the gripper actuator.

3.1 NSGA-II-cum-Golden-Section Search and Results

We use the identical algorithm as that used in the case of Gripper-I. The following parameter values are used:

1. Variable bounds are as follows: $10 \leq a \leq 250$, $10 \leq b \leq 250$, $100 \leq c \leq 250$, $10 \leq d \leq 250$, $10 \leq l \leq 250$
2. Other parameters are as follows: $Y_{\min} = 50 \text{ mm}$, $Y_{\max} = 100 \text{ mm}$, $Y_G = 150 \text{ mm}$, $Z_{\max} = 50 \text{ mm}$, $P = 100 \text{ mm}$,
3. NSGA-II Parameters are exactly the same as in the case of Gripper-I.

Another study on a number of solutions, it was found that the gripping force F_k has a single maximum point, which is found using the golden section method. The minimum of F_k lies usually on one of the extreme values of z . Figure 17 shows a typical variation of F_k on the entire range of z values used in this study.

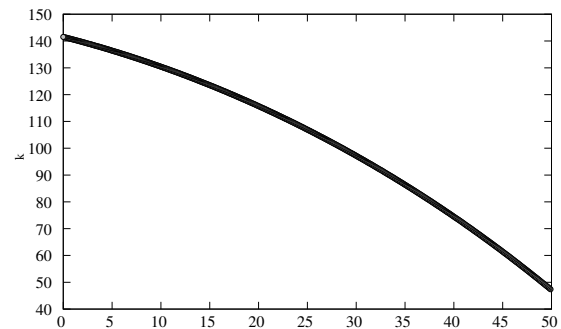


Figure 17: A typical variation of gripping force F_k with the displacement z for Gripper-II.

Figure 18 shows the trade-off frontiers obtained by the NSGA-II procedure after 1,000 generations. A comparison with the original study [10] reveals that the frontier obtained using NSGA-II completely dominates the front reported in the original study. The use of an efficient constraint handling strategy, an accurate methodology for identifying minimum and maximum of gripping force, and modular operations of NSGA-II allowed better non-inferior solutions to be found.

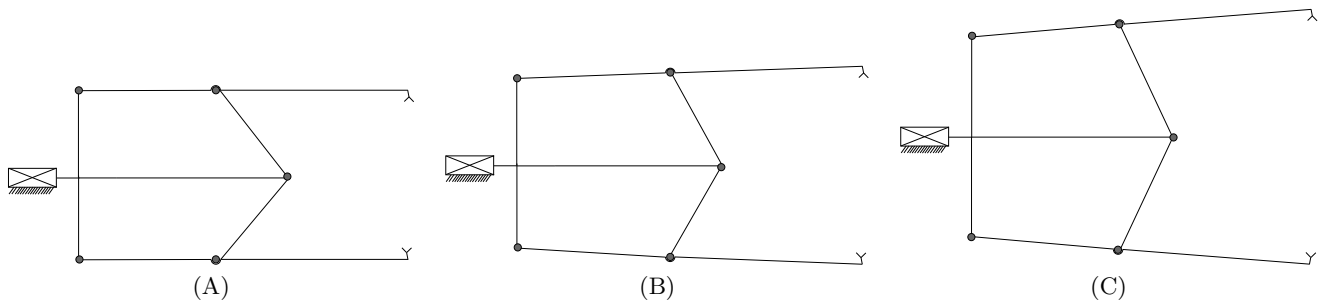


Figure 19: Three NSGA-II solutions selected from trade-off frontier for Gripper-II.

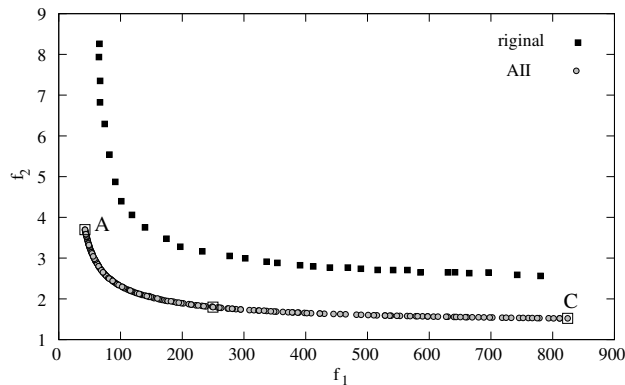


Figure 18: Trade-off frontiers obtained by NSGA-II and the original study are compared for Gripper-II.

Figure 19 shows three widely distributed configurations, including two extreme trade-off solutions (A and C).

3.2 Innovization Study on Gripper-II

Like in Gripper-I, here we study the obtained NSGA-II solutions for any hidden design principles. Figures 20, 21, 22, 23, and 24 show the variation of variables for different values of the second objective function (force transformation ratio). The dimension a takes an identical intermediate value for all trade-off solutions. The dimensions c and l take their upper bound value for all trade-off solutions. The dimensions b and d reduce with force transmission ratio (f_2) in the following manner:

$$b = 270.426f_2^{-0.213}, \quad (7)$$

$$d = 138.380f_2^{-0.149}. \quad (8)$$

These variations in the range of their allowable range is rather small, but are enough to cause a trade-off between the two objectives considered in this study. The reduction in link-length b with increasing f_2 can be explained as follows. Since b and c act like a balance with end forces proportional to P and F_k , respectively, for a fixed c , f_2 which is the ratio of P/F_k is inversely proportional to b .

4. COMBINED CONSIDERATION OF GRIPPERS I AND II

After finding the trade-off solutions for both grippers independently, an user may wonder which of the two gripper problems is better from the point of view of two objectives

used in this study (minimum variation in gripping force and minimum force transmission ratio). Although they look similar, both grippers are fundamentally different in their operations. Gripper-I closes its grip when the actuation takes place towards right, whereas in Gripper-II it happens when it is pushed left. Moreover, Gripper-II has fewer links than Gripper-I. For the constraint sets considered here, trade-off plots (Figures 6 and 18) suggest that Gripper-II causes a larger variation in gripping force F_k compared to that in Gripper-I. Also, for Gripper-I, the force transmission ratio is better. Thus, in general, Gripper-I can be considered to be a better design than Gripper-II. Figure 25 shows the trade-off frontiers from Gripper-I and Gripper-II studies.

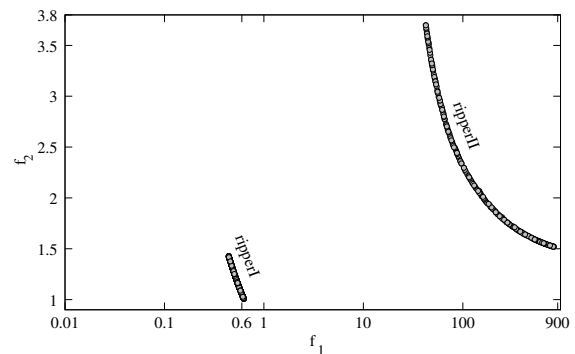


Figure 25: Trade-off frontiers of the two gripper studies are shown.

It is clear from the figure that Gripper-I solutions outperform Gripper-II solutions, hence Gripper-I can be considered as a better design solution than Gripper-II.

5. CONCLUSIONS

In this paper, we have considered the design optimization of two robot gripper configurations, each having a number of non-linear and geometrical constraints. Another difficulty of these problems is that the objectives and constraints involve a couple of single-variable optimization tasks, thereby making the problem a nested optimization problem. Here, we have used the golden section search method for solving the inner optimization task and the constrained NSGA-II procedure for the bi-objective optimization task.

First, the obtained trade-off frontier for each configuration has been found to outperform the front reported in another study on the same problems. Second, the trade-off solutions

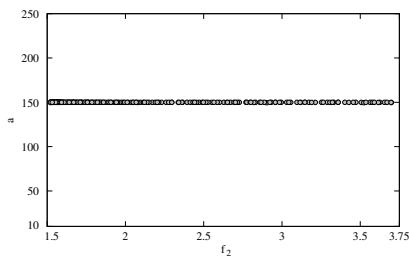


Figure 20: Variation of link length a with force transformation ratio for Gripper-II.

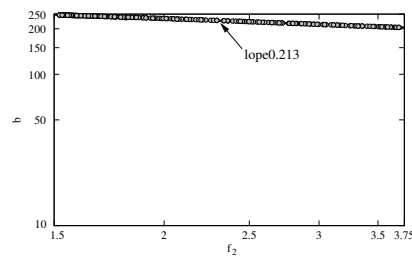


Figure 21: Variation of link length b with force transformation ratio for Gripper-II.

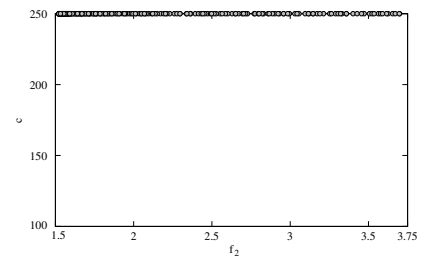


Figure 22: Variation of link length c with force transformation ratio for Gripper-II.

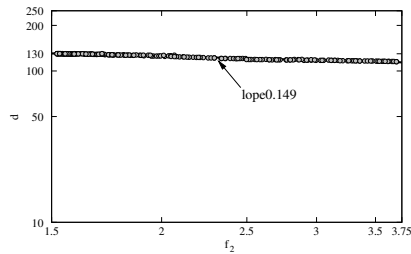


Figure 23: Variation of link length d with force transformation ratio for Gripper-II.

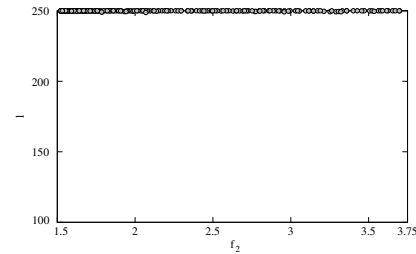


Figure 24: Variation of link length l with force transformation ratio for Gripper-II.

have been analyzed to decipher salient design principles associated with them. Interestingly, all the trade-off solutions have been found to vary in only one of the link-lengths and other variables have been found to remain constant in all trade-off solutions. Such knowledge about trade-off solutions at large are valuable to the designers.

From the two sets of trade-off solutions obtained by our proposed approach, it has also become clear that Gripper-I configuration is better than Gripper-II from a perspective of both objectives. Thus, our optimization task has finally suggested the use of Gripper-I for a possible implementation.

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6. REFERENCES

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