THE BEES' ALGORITHM FOR DESIGN OPTIMIZATION OF A GRIPPER MECHANISM

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Abstract

In this paper, a gripper mechanism is optimized by using bees' algorithm (BA) to compare with Non-dominated Sorting Genetic Algorithm version II (NSGA-II). The procedure of BA is proposed. The superiority of BA is illustrated by using results in figures and tables. A sensitivity analysis using correlation test is executed. The effectiveness coefficients of design variable for the objectives are provided. Consequently, the effectual design variables and the genuine searching method of BA are clearly evaluated and discussed. The BA provides dispersed and the least crowded Pareto Front population for solution in the shortest duration. Therefore, the best solutions are selected based on curve fitting. The closest solutions to the fitted curve are selected as the best in the region.

Keywords: Heuristic Optimization, The bees' Algorithm, Gripper Mechanism, NSGA II.

1. Introduction

As the robotic researches increase, gripper mechanisms for robotic applications have been intensively studied for longer than last two decades[1]. Designing a gripper mechanism needs an optimization process to determine link lengths of mechanism by forming an objective[2]. An optimization problem of gripper mechanism has multiple and conflicting objectives with complex search space. Therefore, solution of the problem is highly difficult with conventional optimization methods. The intelligent optimization methods are generally used for gripper mechanism optimization problems.

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The paper consists of five sections. In section 1, a literature search was proposed. In section 2, the mechanism, objectives, constraints and parameters were briefly presented. In section 3, the bees' algorithm was mentioned. In section 4, results were illustrated. The conclusions were given in section 5.

A proposition to solve a gripper optimization problem with five objectives, nine constraints and seven variables by using Multi-objective Genetic Algorithm (MOGA), Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) and Multi-objective Differential Evolution (MODE) was carried out in [3]. The process had three stages. From these three stages, a Pareto optimal front were generated. Best values were selected. As a consequence of comparison between the three algorithms, MODE was found as the best in terms of minimum effort, solution spread measure and algorithm effort. But NSGA-II performed the best number of solutions with high value of ratio of non-dominated individuals. Therefore, NSGA-II was best for several solutions demanded problem.

An evolutionary search algorithm for a gripper optimization problem of six objectives, eight variables and eleven constraints was used by [4]. In the study, parameters of a gripper B02 made by Global Modular Gripper were optimized. The parameters of the gripper were successfully optimized. Between 110-135 mm distances of gripper ends, the change of the force in the ends of gripper were 50N.

A four-bar slider-crank mechanism for a gripper was modeled in terms of geometrical, kinematical and dynamical [5]. So that, the force in the end of the gripper mechanism and the dimensional parameters were derived. Force transmission ratio and the difference between F_{max} and F_{min} along the actuating distance were determined as objective functions. Nine geometrical inequality constraints and six variables were generated. NSGA-II was used to optimize objectives and parameters. Ultimately, two of the parameters were found the most effective on objective functions.

An optimal design of an under-actuated tendon-driven robotic gripper with two 3-phalange fingers and a geometric design optimization method to achieve a stable grasp performance was presented [6]. The problem has twenty-two design variables. The genetic algorithm is applied to addressing the optimization problem. Practical experiments are performed as well to validate the proposed approach.

A study regarding optimization and demonstration on the behavior of a tendon-driven robotic gripper performing fingertip and enveloping grasps was executed [7]. The gripper consists of two fingers, each with two links, and is actuated using a single active tendon. The optimization problem for the gripper design was derived. The optimization was performed using a combination of random search and gradient descent with numerical gradient computation.

A new method was presented to improve the kinematics of robot gripper for grasping in unstructured environments, such as space operations [8]. The main goal is to improve kinematic structure of gripper to increase the grasping capability of large objects, decrease the contact forces and makes a successful grasp of various objects in unstructured environments. Two objective functions were optimized. Experimental tests were performed to examine the effectiveness of the hand in unstructured tasks. The results represent that the successful grasp range is improved about 30% and the contact forces is reduced approximately 10% for a wide range of target object size.

A design and testing of a variable-aperture, cost-effective gripper, capable of adapting its aperture (grasp width) to different handling demands, without affecting the working-cycle time of the production system was proposed [9]. The genetic algorithm was used for minimization of structural error function subjected to a set of size and geometric constraints such as Grashof and crank rocker conditions. Simulations and preliminary tests showed that this type of design can be a suitable solution to increase flexibility in robotized workcells without increasing the cycle time.

An analysis of mechanisms in two-finger grippers to formulate an optimum design procedure [10]. The design problem has been approached and formulated as a new optimization problem by using fundamental characteristics of grasping mechanisms. In particular, in order to optimize a mechanism for two-finger gripper, an original multi-objective optimum algorithm has been used by considering four different objective functions, such as grasping index, encumbrance of grasping mechanism, acceleration and velocity for finger gripper with respect to the imposed working area. A case study has been reported by using an 8R2P linkage for a proposed two-finger gripper mechanism. Numerical example has been computed to show the soundness of the proposed new optimum design procedure by referring to computational and practical results.

A passively adaptive and underactuated robotic hand was presented [11]. The hand was found potentially reliable for grasping in unstructured environments. An optimization framework was presented for underactuated compliant hands. The approach of study uses a pre-defined set of grasps in a quasistatic equilibrium formulation to compute the actuation mechanism design parameters that provide optimal performance. The method was applied to a class of tendon-actuated hands; for the simplified design of a two-fingered gripper, the global optimum for the design optimization problem was computed. The results of this analysis in the construction of a gripper prototype, which is capable of a wide range of grasping tasks over a variety of objects, were implemented.

A design and analysis of underactuated robotic hands that use tendons and compliant joints to enable passive mechanical adaptation during grasping tasks was presented [12]. A quasistatic equilibrium formulation was used to predict the stability of a given grasp. This method is then used as the inner loop of an optimization algorithm that can find a set of actuation mechanism parameters that optimize the stability measure for an entire set of grasps. Two possible approaches to design optimization using this framework were discussed; one using exhaustive search over the parameter space, and the other using a simplified gripper construction to cast the problem to a form that is directly solvable using well-established optimization methods. Computations were performed in 3-D, allow arbitrary geometry of the grasped objects and consider frictional constraints.

Harmony Search algorithm was presented by combining with non-dominated sorting algorithm for multi-objective optimization problems [13]. The diversity of the population in every predetermined number of iterations was measured. The efficiency of the hybrid algorithm was investigated by using ZDT, DTLZ and CEC2009 benchmarks. Experimental results confirmed the improved performance of the developed hybrid algorithm.

A newly developed polar bear optimization algorithm was presented and analyzed [14]. The adaptation talent of polar bears to harsh winter condition was imitated as an advantage for local and global search, while birth and death mechanism controls the population. Experimental results and analysis with various parameters showed rapid recognition of the area by the relevant population and efficient birth and death mechanism to improve global and local search within the solution space.

A recently developed gray wolf optimization was modified and presented as cellular grey wolf optimizer with a topological structure [15]. A comparison between the developed algorithm and several meta-heuristic algorithms was presented. Experimental results show that the proposed method performs better than the other algorithms on most benchmarks and engineering problems.

A new approach to robust optimal parameter design for a compliant micro-gripper in order to enhance its qualities was proposed [16]. Hybridization of Taguchi method with differential evolution algorithm (HTDE) is integrated to optimize the displacement and frequency, simultaneously. The results showed that the proposed HTDE outperforms the other methods such as AEDE, TGRA, TGA, PSOGSA, and TPSO.

An investigation of five optimization algorithms for simulation-based optimization for robotic tasks was presented [17]. Coordinate Descent, Conjugate Gradient Descent, Nelder-Mead algorithms, BOBYQA algorithm, Radial Basis Function Optimization (RBFopt) algorithm were implemented to handling meat, gripper design optimization for aligning objects and table picking in cluttered scenes. Consequently, they found RBFopt the best in terms of rebust solutions with the fewest simulations.

A new stochastic evolutionary algorithm Backtracking Search optimization Algorithm (BSA) was hybridized with Quadratic approximation and called HBSA for soling unconstrained non-linear, non-differentiable optimization problem [18]. The algorithm was tested by using various test functions and compared the results with five different hybrid algorithm such as Unified particle swarm optimization scheme(UPSO), Fully informed particle swarm (FIPS), Fitness-distance-ratio based particle swarm optimization (FDR-PSO), Cooperative approach to particle swarm optimization (CPSO-H), Comprehensive Learning Particle Swarm Optimizer (CLPSO). Analysis of the values have shown HBSA was statistically more successful than all of the other algorithms compared.

Cuckoo search optimization was applied for free vibration analysis of Timoshenko beams [19]. Experimental and numerical analysis based on iso geometric analysis were presented. The results show that the higher accuracy is achieved by using the optimization algorithm.

In this study, we targeted to contribute an application of BA on gripper design and comparison with NSGA II. There is also no application of constrained BA in literature. The BA is commonly compared with genetic algorithm[20]. BA is characterized by its simplicity, low computational cost, the ability to solve various types of problems and the ease of adoption of the algorithm to suit problems [21].

In the present study, the BA was used to optimize the mechanism of the gripper optimized in [5] due to comparison of two algorithms performance to evaluate performance of BA on a multi-constraint optimization problem. The BA used for a multi objective constraint optimization problem for the first time. In this respect, the study is novel and a beneficial contribution for the literature.

2. The Mechanism and The Objective Functions

The gripping mechanism compose of two symmetrical four-bar slider-crank mechanism. Therefore, half of the whole gripping mechanism is enough to examine for optimization. The mechanism is basically composed of link 2, link 3 and link 4 whose dimensions are symbolized as d_2, d_3 and d_4 shown in Fig. 1.

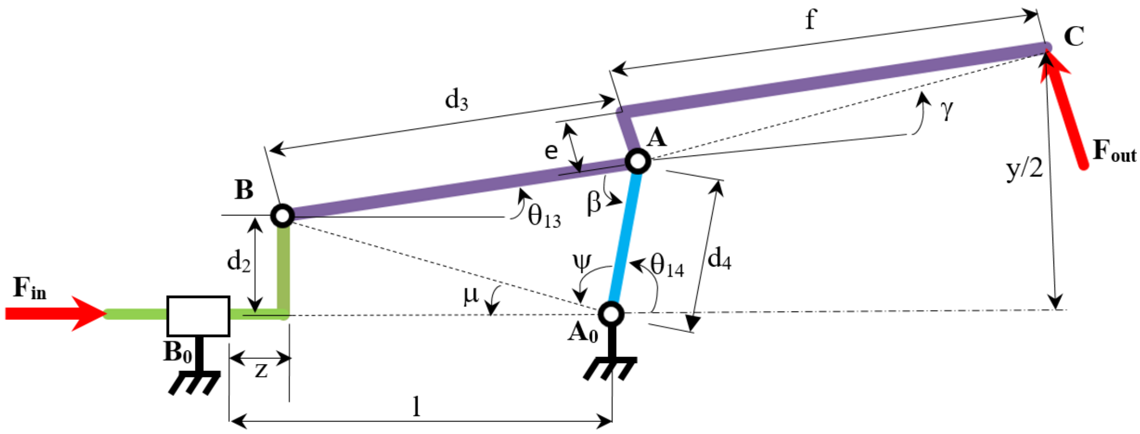

Figure 1. Force distribution, design and geometrical dependency variables of the gripper mechanism[5].

Parameterization of the mechanism for optimization requires geometrical, kinematical and dynamical modelling. For details of modelling, derivations can be referenced to [5]. For the geometrical modelling joints of gripping mechanism were illustrated with the frame as in Fig. 1. In geometrical modelling, location vector of the end-effector and the joint coordinate vector are evaluated. For this study, it is found simpler to model the mechanism by analysis of static equilibrium as in Fig. 2.

The optimization process requires design parameterization and problem formulation. The design parameterization supply design variables $x = (d_2, d_3, d_4, l, e, f)$ for a proper gripper. The design variables and the problem formulation are derived from the modelling process. The geometrical dependencies of the model with design variables are given in equation (1). The design variables and geometrical dependencies of gripper mechanism are shown in figure. 1.

$$\mu = arctan\left(\frac{d_2}{(l-z)}\right)$$
$$\Phi = \pi - \mu$$
$$\Psi = arccos\left(\frac{q^2 + {d_4}^2 - {d_3}^2}{2qd_4}\right) \quad (1)$$
$$\beta = arccos\left(\frac{{d_4}^2 + {d_3}^2 - q^2}{2d_4d_3}\right)$$
$$\Theta_{14} = \Phi - \Psi$$
$$\Theta_{13} = \Theta_{14} - \beta$$

where

$$q = \sqrt{{d_2}^2 + (l-z)^2}$$

The optimization problem is formed by using the force in the end-effector. The formulation for the force may be derived from analysis of static equilibrium on the links of mechanism in the form of design and geometric dependency variables.

The coupler link of the mechanism is under three forces effect and assumed in static equilibrium. Two of the forces direction are known. The force (F_{out}) which is effective for gripping process, is vertical to the coupler link. The force exerted by link 4 to link 3 is in the direction of link 4. So that the direction of the force exerted by link 2 to link 3 can be found by intersecting two former forces as shown in figure. 2. The moment in slider was neglected due to no moment in horizontal axes which is useful for calculation of F_{32}.

From the static equilibrium analysis of link 2, the magnitude of unknown force (F_{23}) on coupler link can be found from equation (2) which is force equilibrium on the horizontal axes by the help of known F_{in}. Finally, F_{out} can be found from equilibrium of moment on the joint A as in equation (3).

$$F_{32} = F_{23} = \frac{P}{2\cos(\Theta_{13} + \alpha)} \quad (2)$$

$$F_{out} = \frac{F_{23} d_3 \sin(-\alpha)}{f} \quad (3)$$

where

$$\alpha = arccos\left(\frac{n^2+{d_3}^2-m^2}{2nd_3}\right)$$

The first objective in equation (4) is the difference between the values of F_{out} in the range of the end-effector displacement. Minimization of this difference is the objective of the optimization problem.

$$f_1(x) = \underbrace{max}_{z} F_{out}(x,z) - \underbrace{min}_{z} F_{out}(x,z) \quad (4)$$

The second objective comprises of the transmission ratio, between F_{in} and F_{out} for Z_{max}. The minimization of transmission ration is the second objective of the optimization problem.

$$f_2(x) = P/\underbrace{min}_{z} F_{out}(x,z) \quad (5)$$

The optimization problem is dependent on decision variables. The decision variables are elements of a vector consisting of design variables. F_{out} has maximum value at the minimum actuating distance and minimum value at the maximum actuating distance as in figure 3.

The constraints of the optimization problem are generated from the geometrical limits of the gripper mechanism. Therefore, the displacement of gripper end is formulated dependent on the actuating distance in equation (5).

$$y(x,z) = 2(d_2 + d_3\sin(\theta_{13}) + \mathrm{c}\sin(\theta_{13})) \quad (6)$$

where

$$c = \sqrt{f^2 + e^2}$$

$$\gamma = \arctan(e/f)$$

The geometric and force parameters are taken as

$Z_{max} = 25\ mm, Y_{max} = 70\ mm,$

$Y_{min} = 30\ mm, Y_G = 100\ mm\ \ P = 95\ N$

1. The minimum displacement between the ends of gripper should be less than the minimum dimension of the gripped object,

$$g_1(x): \quad Y_{min} - y(x, Z_{max}) > 0 \quad (7)$$

2. The distance between the gripper ends at the maximum actuating distance should be greater than zero,

$$g_2(x): \quad y(x, Z_{max}) > 0 \quad (8)$$

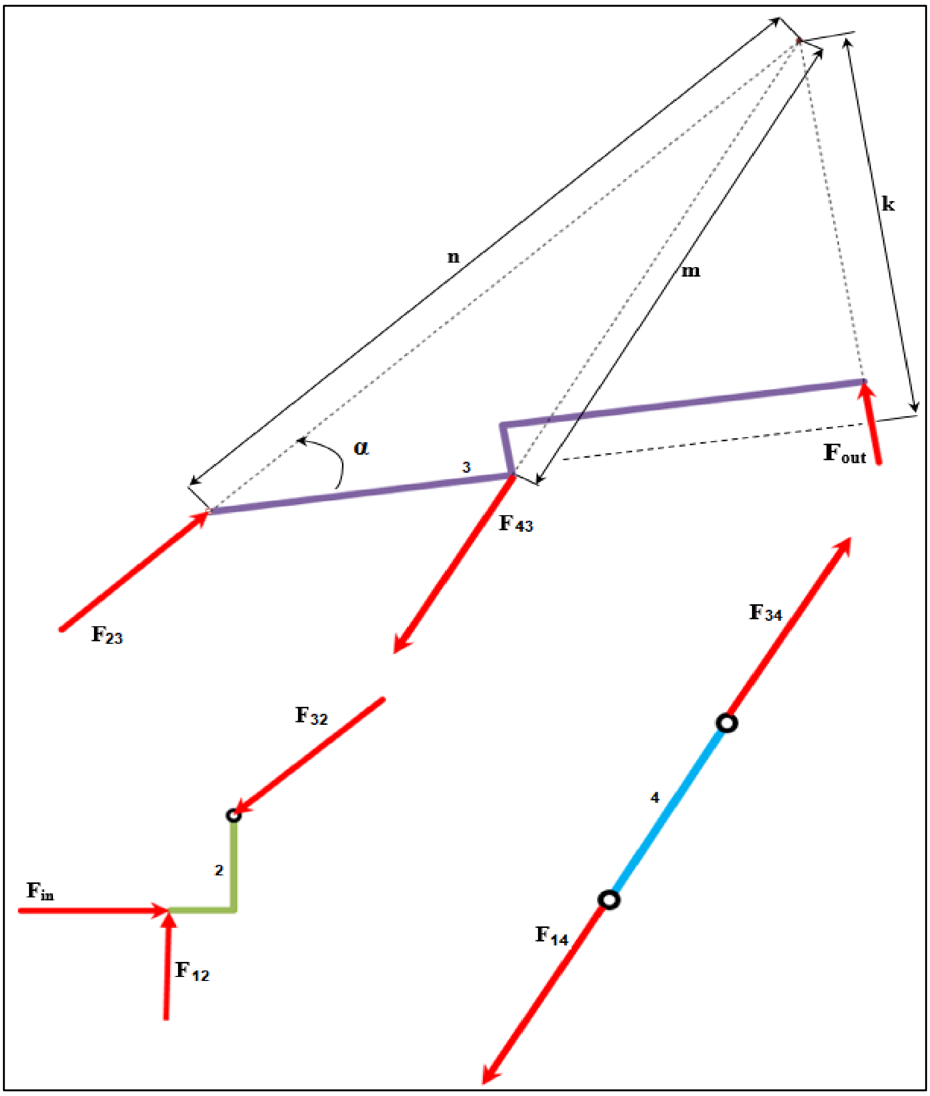

Figure 2. Force equilibrium on mechanism links.

3. The maximum distance between the gripper ends at the no actuating distance should be greater than maximum dimension of gripped object.

$g_3(x)$: $y(x,0) - Y_{max} > 0$ (9)

The maximum distance between the gripper ends should be greater than or equal to the distance between the gripper ends at the minimum actuating distance.

$g_4(x)$: $Y_G - y(x,0) \geq 0$ (10)

4. The maximum actuating distance should be smaller than the design variable l.

$g_5(x)$: $l - Z_{max} > 0$ (11)

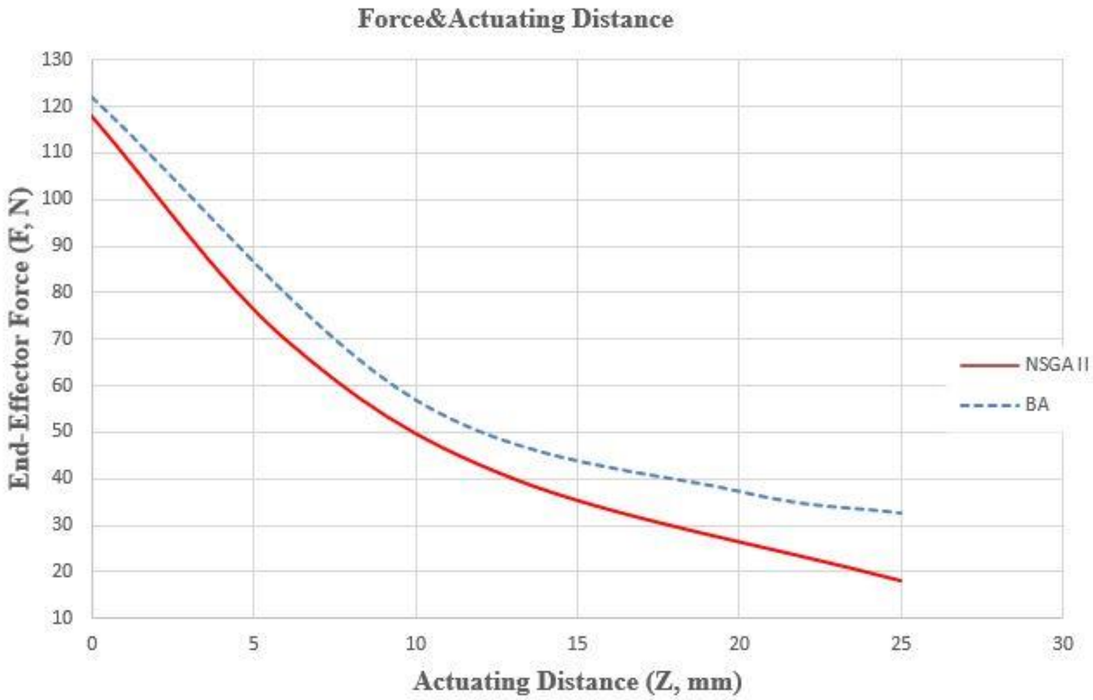

Figure 3. Comparison of algorithms for variation of force F_{out} with the displacement z for a typical design vector x

5. For permanent motion of the output link of the mechanism in the clockwise direction, the angle β should be smaller than π/2 at the minimum actuating distance.

$$g_6(x): \beta(z=0) < \frac{\pi}{2} \tag{12}$$

6. A stable gripping process requires the absolute value of declination angle α smaller than π/36.

$$g_7(x): |\alpha| < \pi/36 \tag{13}$$

7. The input of arcos function in equation (1) should be smaller than one. For verification of triangle condition in $\overset{\Delta}{OAB}$.

$$\left|\frac{g^2 + {d_4}^2 - {d_2}^2}{2gd_4}\right| < 1 \tag{14}$$

After simplification and substitution of g, and rearrangement,

$$g_8(x):\ {d_2}^2 + (l - Z_{max})^2 - (d_4 - d_2)^2 > 0$$

$$g_9(x): (d_3 + d_4)^2 - {d_4}^2 + l^2 > 0 \tag{15}$$

8. The geometric bounds of link lengths, or design variables, (in mm), are

$10 \leq d_2 \leq 50,\quad 10 \leq d_3 \leq 60,\quad 10 \leq d_4 \leq 50$

$10 \leq l \leq 50,\quad 5 \leq e \leq 15,\quad 50 \leq f \leq 100$

Briefly, the optimization can be expressed as

$x^* = (d_3{}^*, d_4{}^*, d_5{}^*, l^*, e^*, f^*)$ which can satisfy

$g_k(x) \quad k = 1, .., 9$

$f(x^*) = \min[f_1(x), F(x, Z_{max})]$

3. The Bees' Algorithm

The BA is an intelligent swarm-based optimization tool [22]. Regarding the algorithm, the parameters to be set, namely: number of scout bees (n), number of sites selected out of n visited sites (m), number of best sites out of m selected sites (e), number of bees recruited for best e sites (nep), number of bees recruited for the other (m-e) selected sites (nsp), initial size of patches (ngh) which includes site and its neighborhood and stopping criterion[23]. Originally in the present study, the randomly generated scout bees as design variables are interchanged to calculate fitness values for harmonization process.

The algorithm starts with the determination of algorithm parameters. "n" number of design variables are placed randomly in the determined range. Differently in this study, the design variables are harmonized and controlled if they fit the geometrical constraints after each random design variable production. The value of the objective functions calculated from randomly placed design variables are increasingly sequenced. The sequence is investigated within the three following processes[24].

The first "e" number of sequences are chosen for neighborhood search. The neighborhood search is executed by randomly generated "nep" number of neighbors with the "ngh" criterion from the elected design variables. Thereafter, the generated neighbors are harmonized. The values of objective functions for neighbors are sequenced incrementally. Among the neighbors, the best "e" values are selected[24].

The (m-e) number of the sequence are selected for neighborhood search. The previous process is similarly repeated with "nsp" number of neighbors. Among the neighbors, the best "m-e" values are selected. The rest of the "n" number sequenced values are randomly searched, sequenced as in figure 4. This process repeats until iteration ends[24].

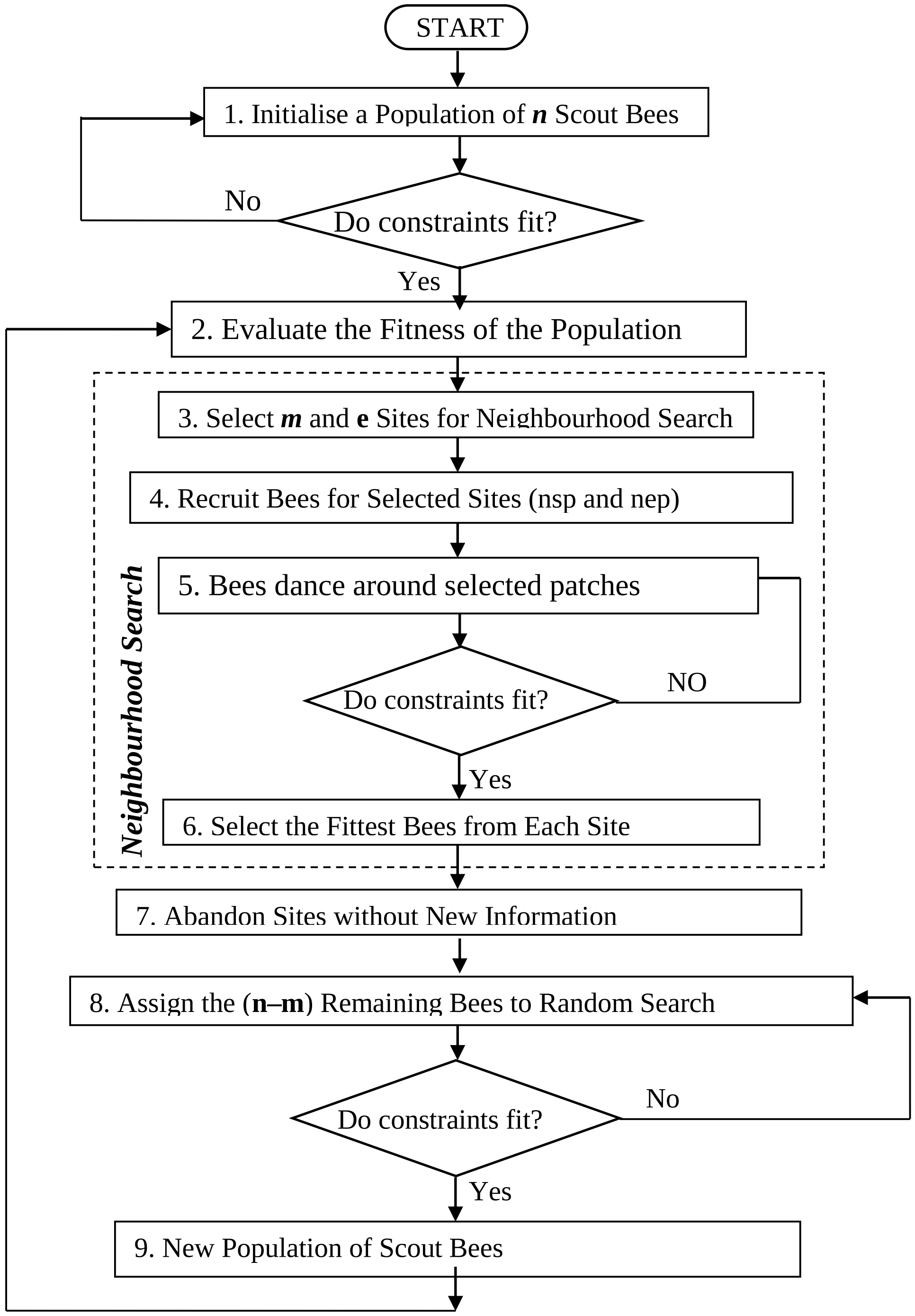

Figure 4. The Bees' Algorithm procedure

4. The Results

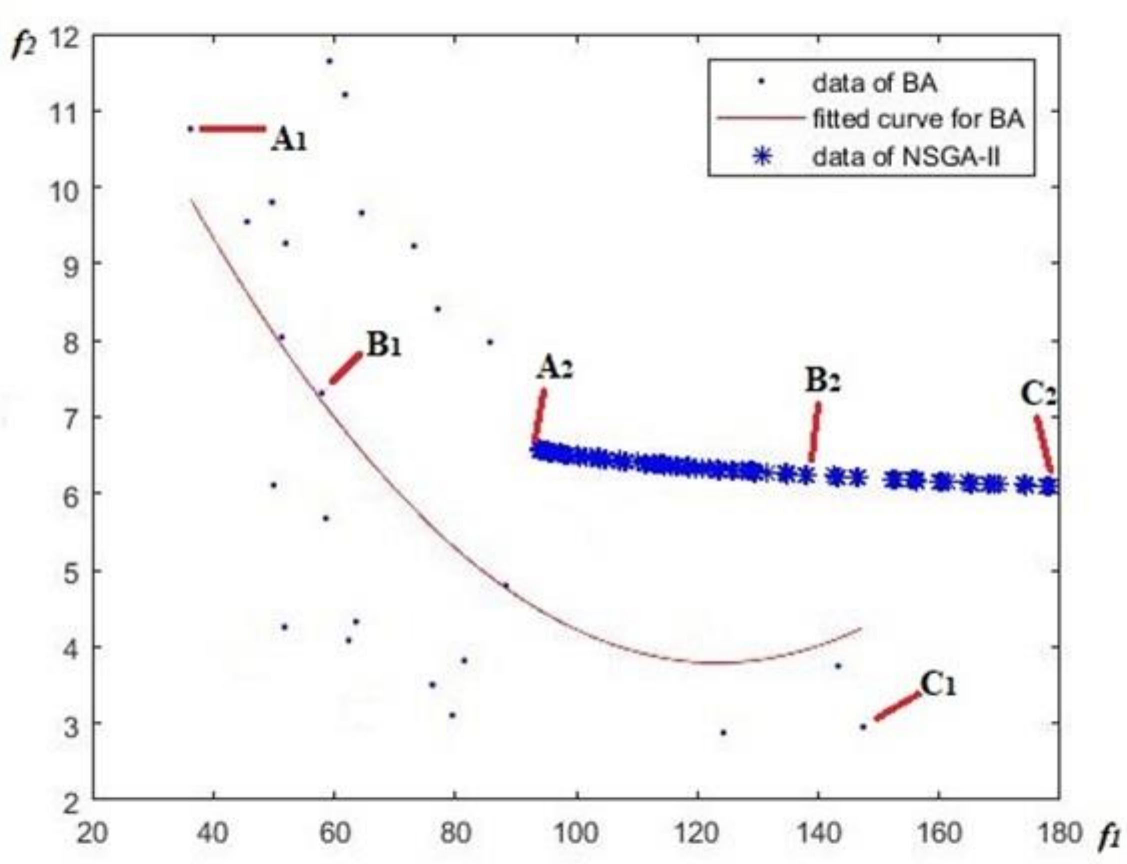

Figure 5. Set of optimal solutions obtained using the BA and NSGA-II

Table 1. The best three converged values of the bees' algorithm.

	f_2	f_1	d_2	d_3	d_4	l	e	f
A_1	10,9	39,55	36,44	59,72	42,91	42,62	5,07	71,34
B_1	7,26	62,21	20,69	44,30	29,26	39,9	7,65	55,12
C_1	2,92	149,44	47,48	50,32	39,70	40,71	10,62	65,16

Table 2. The three selected values from Pareto front of NSGA-II[5].

	f_2	f_1	d_3	d_4	d_5	l	e	f
A_2	6,64	93,81	32,92	19,08	54,73	49,85	5,00	50,00
B_2	6,25	138,9	30,89	18,88	52,31	49,74	5,00	50,00
C_2	6,09	184,2	29,69	18,80	51,28	49,71	5,00	50,00

The two algorithms give Pareto optimal solutions as in figure 5. Contrary to NSGA-II [5], the BA searches variables in scattered spaces and selects the best of the space as in Table 1. Therefore, it has dispersed points on the graph as in figure 5. Moreover, it takes shorter time. In this study, the BA has 24 Pareto optimum solutions with high values in Table 1. The three results of design variables (A, B, C) for f_2 and f_1 values were given as in Table 1-2. The values of B are selected as the best among for the results of two algorithms. The optimization parameters were tuned by the help of literature [25] regarding elapsed time (6,43 s), minimum iteration to the converged value as itr=50, n=20, nsp=10, ngh=0.1, m=10, nep=20, e=5.

When compared with the results of NSGA-II in Table 2 [5], The bees algorithm found bigger transmission ratio and lower differences between forces of actuating distances. The two algorithms performed under a PC specifications Intel® Core™ i7 @ 2.6 GHz, RAM: 16GB, Windows 10 64-bit. Consequently, as the BA takes 6.43 seconds, NSGA-II takes 5.12 minutes for optimization process.

The results of BA are analyzed using correlation analysis method for degree of effect between the design variables and objectives. Therefore, the sensitivity of the design variables is evaluated. We presented the negative and positive effectiveness coefficients of the design variables for the objectives (see Fig. 6-7). The effects of design variables on the first objective function; e has the highest influence among the design variables. d_3 is more influential design variable among the rest of design variables. d_4 and l have a negative effect. f and d_2 have the least impact.

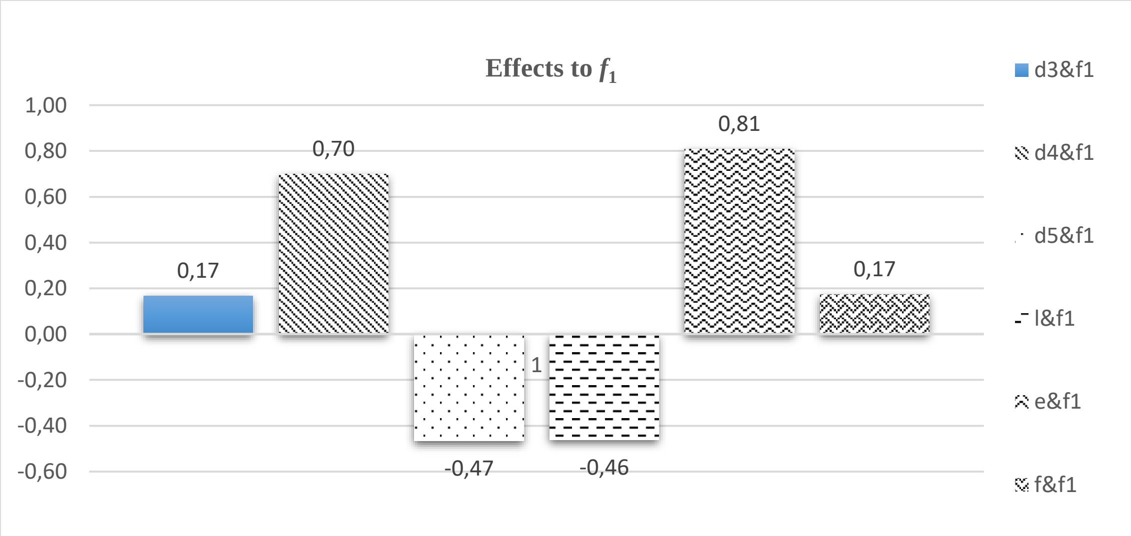

Figure 6. Sensitivity of f_1 to design variable variations of BA.

The effects of design variables on the second objective function; d_4 and l have negative the highest effect. d_3 and e are more influential than f and d_2 positively. The sensitivity analysis showed that d_3 and e are the most influential on the first objective. d_4 and l have the highest impact on the second objective function. Thus, those four design variables are limited in a proper interval of tolerance from ISO 284.

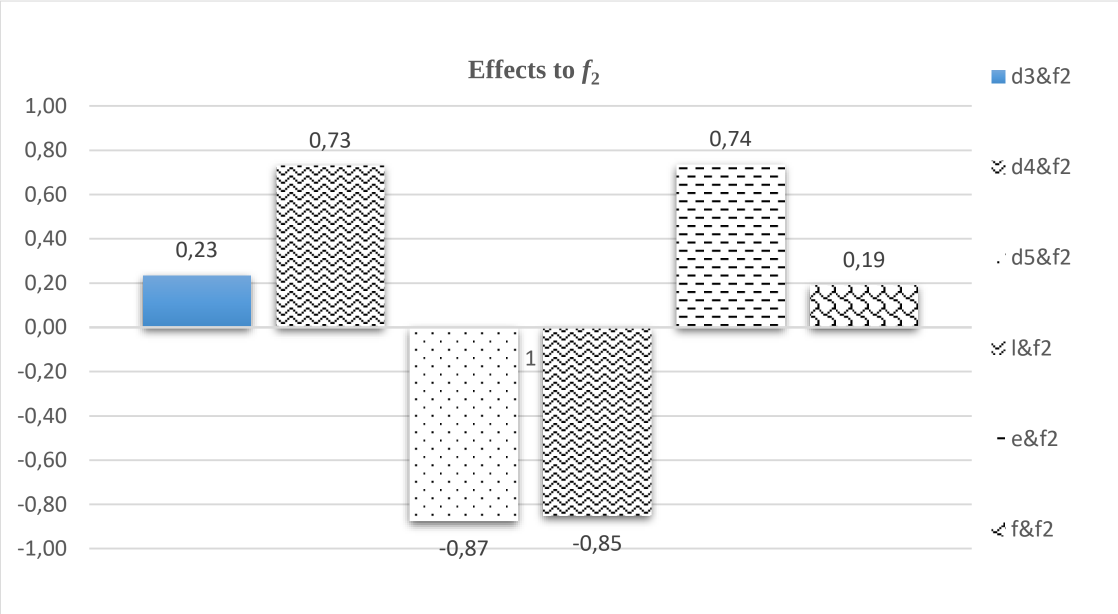

Figure 7. Sensitivity of f_2 to design variable variations of BA.

5. Conclusion

This study has proposed a comparison between BA and NSGA-II for optimization of a mechanism dimensions. The modelling stage, constraints and objectives are briefly mentioned. The algorithm is illustrated as a flow chart. Finally, the results are compared. The goal of this paper is to prove the superiority of searching method of the BA and its application on constraint problem of mechanism design. The results verified that the BA has outstanding feature for searching optimal points. The superiority of BA is the searching process for the best design variables. The sensitivity analysis showed that four design variables are highly influential on objectives.

The oncoming work on the study may be to use the BA for spherical mechanism optimization. A harmonization process can be applied for the algorithms as well. The polar bear and gray wolf algorithms may be also hybridized by the harmonic process. Therefore, the current performances of aforementioned algorithms may be analyzed.

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Appendix

1. Fig. 1. Configuration for solution A_1
2. Fig. 2. Configuration for solution B_1
3. Fig. 3. Configuration for solution C_1

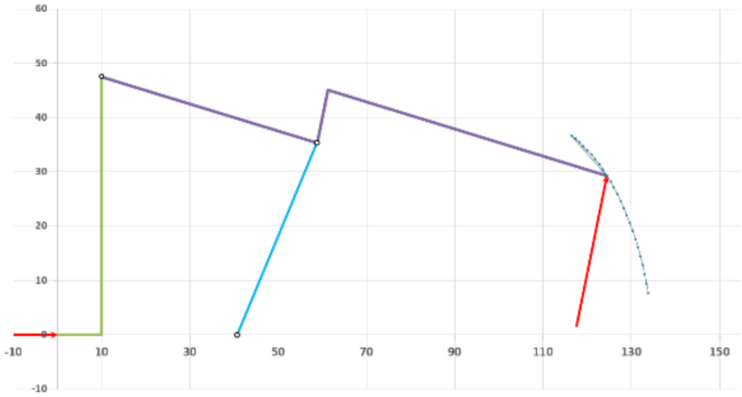

Figure 1. Configuration for solution A_1

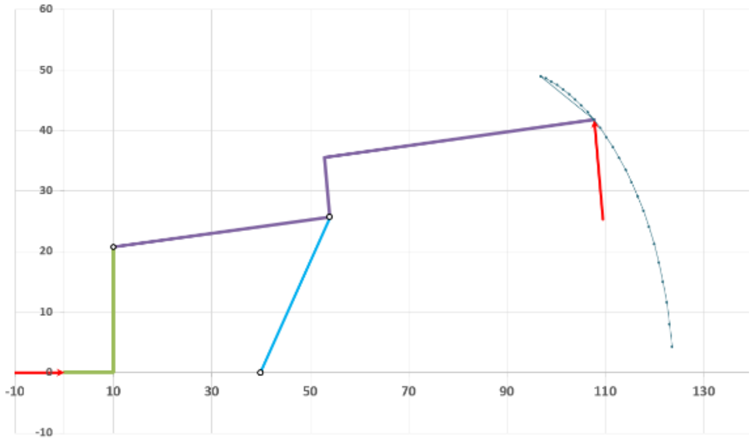

Figure 2. Configuration for solution B_1

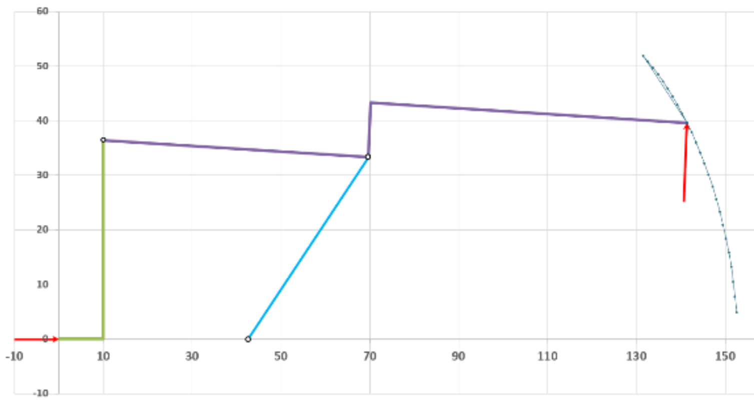

Figure 3. Configuration for Solution C_1