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Matlab's GA and Optimization Toolbox: A Fourbar Mechanism Application

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Abstract: This study presents an optimization approach for synthesis of planar mechanisms. A four bar mechanism is chosen for an application example. This mechanism is studied with the constraints assigned. Genetic Algorithm (GA) is applied during optimization study. GA in Optimization Toolbox is then compared with nonlinear constrained numerical optimization command; fmincon in Matlab©. Different case studies are performed by considering different target points. These mechanisms are drawn using Excel© spread sheet to see their animations. An optimization example is presented here. Performances of both algorithms are then compared in terms of coupler curves precision points. Their use in designing a four bar mechanism is explored for its further use.

Keywords: *Four bar mechanism, Mechanism synthesis, Optimization, Genetic algorithm.*

1. Introduction

The purpose of this study is to perform a comparative study on synthesis of mechanical linkages using genetic algorithm. Some recent studies on the subject covering more than ten years are surveyed. Since the optimum synthesis of a mechanism requires a repeated analysis to find the best possible one to meet requirements, dimensional synthesis will be preferred here. A simulation study will be performed on a four bar linkage. The linkage parameters will be tabulated as a guide for the user. The computational synthesis methods are also applied [1, 2, 3]. The science of motion is related with the analysis and synthesis of mechanisms in study of Kinematics. It also deals with the relative geometric displacements of points and links of a mechanism. Dimensional Synthesis looks for determining optimal dimensions of a prescribed type of mechanism. The type and dimensional levels are the main factors in the mechanisms for the study of kinematic synthesis of mechanisms [4-8].

The objective is to apply an evolutionary method for synthesis of planar mechanisms and present a design guide for its use in linkage mechanisms. The evolutionary process is not related with the results which are obtained from enumeration of mechanisms. Some algorithms are included in Matlab as toolbox facility. This study is organized as follows; first part outlines an introduction with synthesis of planar mechanism, statement of problem. Literature survey is also given on mechanism synthesis using GAs. Matlab Optimization Toolbox is introduced with Genetic algorithm Toolbox. Some illustrative examples are done on optimization based synthesis problems for 4 bar mechanism. An example application is given by using two optimization approach based on Matlab environment. Matlab Optimization Toolbox with constrained optimization is compared with Genetic Algorithm Toolbox (GA).

2. Survey on Synthesis on Planar Mechanisms

Many studies are seen on optimization based synthesis and optimization using GAs. They are included in the following part, and appeared with the years where the studies were performed [9-11].S. Hoskins and G.A Kramer have previously introduced use of ANNs with optimization techniques (Levenberg-Marquardth Optimization) to synthesize a mechanical linkage generating a user-specified curve [12]. M.H.F.Dado and Y.S.Mannaa have described the principles for an automated planar mechanism dimensional synthesis, [13]. R.C. Blackett has presented a technique for the optimal synthesis of planar five link mechanisms in Master's Study [14]. P.S. Shiakolas et al. have presented representative examples utilizing Matlab through a web browser interface [15]. J. A Cabrera et al. have dealt with solution methods of optimal synthesis of planar mechanisms [16]. R. Bulatovic and S.R Djordjevic have performed optimal synthesis of four bar linkage by method of controlled deviation with Hooke-Jeeves's optimization algorithm [17]. Laribi et al. have proposed a combined Genetic algorithm- Fuzzy Logic Method (GA-FL) to solve the problem of path generation in mechanism synthesis [18]. K.G. Cheetancheri et al. have presented a study on Computer Aided Analysis of Mechanisms Using Ch Excel, [19]. J.F. Collard et al. have presented a simple approach to optimize the dimensions and the positions of 2D mechanisms for path or function generator synthesis [20]. H.H. Cheng et al. have presented a study on a web-based mechanism analysis and animation [21]. J. Xie et al. have proposed an approach to kinematics synthesis of a crank rocker mechanism. Coupler link motions passing from a prescribed set of positions are generated [22]. Liu et al. has presented a new approach using the framework of genetic algorithms (GAs) [23]. S .Erkaya and İ. Uzmay have presented a study on dimensional synthesis for a four bar path generation with clearance in joints [24]. N.N. Zadeh et al. have used hybrid multi-objective genetic algorithms for Pareto optimum synthesis of four-bar linkages. Objective functions are taken tracking error (TE) and transmission angles deviation (TA) [25]. S.K. Archaryya et al. have performed

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a study on performance of Evolutionary Algorithms (EAs) for four-bar linkage synthesis. Three different evolutionary algorithms such as GA, Particle Swarm Optimization (PSO), differential Evolution (DE) have been applied for synthesis of a four bar mechanism [26]. A. Kentli et al. have presented a study on genetic coding application (GCA) to synthesis of planar mechanisms [27]. K. Sedlaczek and P. Eberhard have presented a study on extended Particle Swarm Optimization technique based on the Augmented Lagrangian Multiplier Method [28]. F. Pennunuri et al. have given optimal dimensional synthesis for planar mechanisms using differential evolution (DE) with four examples, Pennunuri et al. [29]. Erdogan has performed a comparative study on GA and fmincon for planar mechanisms in his thesis. A four bar mechanism is analysed. [30].

3. Motion, Path and Function Generation

The dimensional synthesis problems can be broadly classified as motion generation, path generation and function generation [1-3].
(i) Motion Generation: a rigid body has to be guided in a prescribed manner in motion generation. Motion generation is related with links controlling the links in the plane. The link is required to follow some prescribed set of sequential positions and orientations.
(ii) Path Generation: If a point on floating link of the mechanism has to be guided along a prescribed path, then such a problem is classified as a problem of path generation. Path Generation controls the points that follow any prescribed path.
(iii) Function Generation: The function parameters (displacement, velocity, acceleration etc.) of the output and input links are to be coordinated to satisfy a prescribed functional relationship. The Function Generation is related with functional relationship between the displacement of the input and output links [23].

3.1. Four Bar Mechanism

A four bar mechanism has four revolute joints that can be seen with numerous machinery applications. There is a relationship of the angular rotations of the links that is connected to the fixed link (correlation of crank angles or function generation). If there is not any connection to the fixed link which is called the coupler link. This position of the coupler link can be used as the output of the four bar mechanism. The link length dimensions determine the motion characteristics of a four bar mechanism according to the Grashof's theorem. The link lengths are the function of the type of motion and are identified for a four bar chain as follows [2]. Here l is the longest link length, s is the shortest link length, p and q are the two intermediate link lengths. The input-output equation of a four bar is taken as by looking at link lengths. Figure 1. shows all possible mechanism configurations as crank rocker, double rocker and double crank.

4. Kinematics of Four Bar Mechanism

The kinematic analysis of a four-bar mechanism is considered first. Figure 2 shows four bar mechanism in general coordinate system [16, 26]. The design procedure of a four-bar linkage starts with the vector loop equation referring to Figure 2. The position vectors are given as $\vec{R}_1, \vec{R}_2, \vec{R}_3, \vec{R}_4$. The offset angle is notated by θ_0 and the input angle is θ_2. The position vectors are used to get complete four bar linkage as in Eqn.(1).

$$\vec{R}_2 + \vec{R}_3 = \vec{R}_1 + \vec{R}_4 \qquad (1)$$

The complex number notation can be substituted next by using scalar lengths of the links as r_1, r_2, r_3 and r_4. It is given in Eqn. (2)

$$r_2 e^{i\theta_2} + r_3 e^{i\theta_3} = r_1 e^{i\theta_0} + r_4 e^{i\theta_4} \qquad (2)$$

Here θ_3 and θ_4 the angles to be found. They can be expressed as

$$\theta_3 = f\{r_1, r_2, r_3, r_4, \theta_2, \theta_0\} \text{ and}$$

$$\theta_4 = f\{r_1, r_2, r_3, r_4, \theta_2, \theta_0\} \qquad (3)$$

Eqn. (2) is expressed with its real and imaginary parts with assumption of θ_0=0, then the real and imaginary parts are written as in Eqn's (4.1) and (4.2)

$$r_2 \sin\theta_2 + r_3 \sin\theta_3 = r_4 \sin\theta_4 \qquad (4.1)$$

$$r_2 \cos\theta_2 + r_3 \cos\theta_3 = r_1 + r_4 \cos\theta_4 \qquad (4.2)$$

$$K_1 \cos\theta_3 - K_4 \cos\theta_2 + K_5 = \cos(\theta_2 - \theta_3) \qquad (5.1)$$

$$K_1 \cos\theta_4 - K_2 \cos\theta_2 + K_3 = \cos(\theta_2 - \theta_4) \qquad (5.2)$$

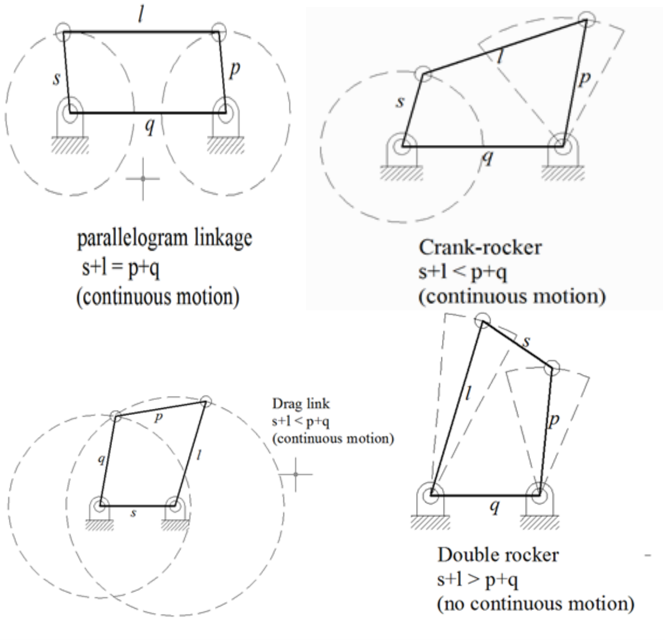


Figure 1. Possible Four bar configurations

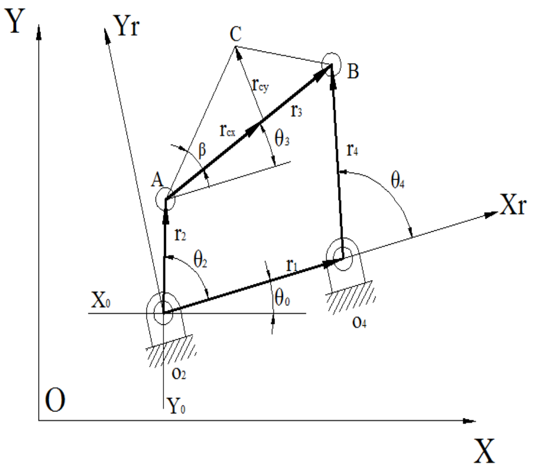


Figure 2. Four bar mechanism in general coordinate system.

K_1, K_2, K_3, K_4 and K_5 are found as;

$$K_1 = \frac{r_1}{r_2},\ K_2 = \frac{r_1}{r_4},\ K_3 = \frac{r_2^2 - r_3^2 + r_4^2 + r_1^2}{2 r_2 r_4},\ K_4 = \frac{r_1}{r_3},$$

$$K_5 = \frac{r_4^2 - r_1^2 - r_2^2 - r_3^2}{2 r_2 r_3} \qquad (6)$$

The angles are then given ;

$$\theta_{3_{(1,2)}} = 2\tan^{-1}\left(\frac{-B \pm \sqrt{B^2 - 4AC}}{2A}\right)$$

$$(7)\quad \theta_{4_{(1,2)}} = 2\tan^{-1}\left(\frac{-E \pm \sqrt{E^2 - 4DF}}{2D}\right)$$

(8)

In above equations; ± sign refers to two different configurations of the four bar mechanism. A, B, C, D, E and F expressions are then written as

$$A = \cos\theta_2 - K_1 - K_2\cos\theta_2 + K_3, \qquad B = -2\sin\theta_2,$$

$$C = K_1 - (K_2 + 1)\cos\theta_2 + K_5 \qquad (9)$$

$$D = \cos\theta_2 - K_1 + K_4\cos\theta_2 + K_5, \qquad E = -2\sin\theta_2,$$

$$F = K_1 + (K_4 - 1)\cos\theta_2 + K_5$$

Again referring to Figure 2, the reference frame is taken as $O_2 X_r Y_r$, and the design variables for the mechanism are taken as $r_1, r_2, r_3, r_4, r_5, r_{cx}, r_{cy}, \theta_0, x_0, y_0$. By taking, the coupler position (C) can be written as

$$C_{xr} = r_2\cos\theta_2 + r_{cx}\cos\theta_3 - r_{cy}\sin\theta_3 \qquad (10.1)$$

$$C_{yr} = r_2\sin\theta_2 + r_{cx}\sin\theta_3 - r_{cy}\cos\theta_3 \qquad (10.2)$$

In previous notation, by taking OXY then;

$$\begin{bmatrix} C_x \\ C_y \end{bmatrix} = \begin{bmatrix} \cos\theta_0 & -\sin\theta_0 \\ \sin\theta_0 & \cos\theta_0 \end{bmatrix} \begin{bmatrix} C_{xr} \\ C_{yr} \end{bmatrix} + \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \qquad (11)$$

Eqn. (11) is later used while performing derivations of the goal function for the mechanism.

5. Optimum Synthesis of Four Bar Mechanism

There is an increase in computer technology which has permitted us in developing routines that apply methods to the minimization of a goal function. There is a common goal function that is the error between the points tracked by the coupler (crank-rocker) and its desired trajectory in general. The aim is to minimize the goal function applying optimization techniques here. Initially the link lengths are chosen according to the Grashof's Theorem. Many cases a continuous rotary input is applied and the mechanism must satisfy the Grashof criteria. The first part computes the position error in the objective function. The sum of the squares of the Euclidean distances between each point is defined and a set of target points indicated by the designer that should be met by the coupler of the mechanism. These points can be written in a world coordinate system as are the target positions on the coupler.

$$C_T^i = \left[C_{xT}^i ; C_{yT}^i\right], \text{ Where } i=1, 2, 3,\ldots,n \qquad (12)$$

The variables can be optimized in case of problem without prescribed timing. Structural error is the error between the mathematical function and the actual mechanism. Accordingly, the first part of goal function can be expressed by minimize:

$$f_{obj} = \sum_{i=1}^{N}\left[\left(C_{xT}^i - C_x^i\right)^2 + \left(C_{yT}^i - C_y^i\right)^2\right] \qquad (13)$$

N represents the number of points to be synthesized. The geometric magnitudes of four-bar mechanism are previously described in Fig. 2. The design variables and the input angle θ2. The second part of goal function is derived from the constraints which are imposed on the mechanism and set as the following:

(i) The Grashof condition allows for full rotation of at least one link.

(ii) The sequence of input angles, θ_2 can be from the highest to the lowest (or the lowest to the highest).

(iii) The range for the design variables should be given.

(iv) The range of variation for the input angle should be given.

The first three conditions are imposed and the fourth condition is taken as to perform full 360° rotation of the crank in the results presented here. In order to use this definition of the problem when the optimization algorithm is implemented, the constraints are retained and the values are assigned to the design variables X.

6. Case Study on Multiobjective Constrained Optimization

The objective function is constrained one for synthesizing four-bar mechanism. Grashof's condition and constraints regarding to sequential (CW or CCW) rotation of the input crank angle. The constraints play an important role in designing a feasible solution of the mechanism. A high number of initial populations are chosen randomly from the given set of minimum and maximum values of the variables so that a considerable amount of them can play in next iteration. This technique unnecessarily increases CPU time and reverses a large amount of memory in the computer. The refinement of population applied here is only for choosing an initial population and the other part of the evolutionary algorithms is kept same. The randomly chosen initial population is modified according to feasibility of making an effective mechanism.

In a randomly chosen variable set, the lengths of the linkage and the crank angle, θ2 are taken. The linkage lengths initially chosen as random, that may satisfy the Grashof's condition. The lengths are reassigned if they fail to satisfy this condition. After that randomly chosen, the input angles are rearranged in CW or CCW with randomly choosing first input angle among the initial generated set to meet the constraints. After these modifications in initial population, a comparatively greater number of strings can be found to make a feasible mechanism or the probability of rejection of strings in next iteration is reduced. *fmincon* command is used for nonlinear and many variables. This is a gradient based search function in Matlab© to solve the constraint problem. To run this program and to perform optimization, it is necessary to have a constrained m-file. Firstly the link lengths are defined as r_1, r_2 , r_3, r_4 . The constraints are defined according to the link lengths which is related with the Grashof's Theorem l-the longest link, s-the shortest link, p, q -two intermediate links as l+s<p+q. So the link lengths are chosen according to these values as the constraints. The constraints are set as $l=r_1$ (the link 1), $s=r_2$ (the link 2), $p=r_3$ (the link 3), $q=r_4$ (the link 4), [30].

6.1. Path generation without timing

Here an example is included to show comparative results on GA and *fmincon*. There are six coupler points required to find out an optimal solution. These points are designed to trace a vertical straight line by changing Y coordinate only. The problem is then defined by;

(i) The design variables are;

$X = \lfloor r_1, r_2, r_3, r_4, r_{cx}, r_{cy}, \theta_2^i \rfloor$,Where i=1, 2,…, N and N=6

(ii) Target points are chosen as:

$$\left[C_{xT}^i, C_{yT}^i \right] = [(20{,}20),(20{,}25),(20{,}30),(20{,}35),(20{,}40),(20{,}45)]$$

(iii) Limits of the variables;

$r_1, r_2, r_3, r_4 \in [13{,}70]$, $r_{cx}, r_{cy} \in [-60{,}60]$ and $\theta_2^i \in [0, 2\pi]$

where i=1,2,…,N and N=6

(iv) Parameters of GA;

Population Size (PS) = 20, Crossover Possibility (CP) = 0.8, Mutation Possibility-uniform (MP)=0.1, Selection type=Roulette

(v) fmincon conditions;

Maximum iterations= 400

Optimization Toolbox command *fmincon* is compared with GA. The results for GA and *fmincon* are shown in Table 1. Table 2 presents target and traced point with GA. These points are calculated by using Eqns (10.1) and (10.2). Figure 3 shows the target and the traced points in X-Y with GA. Since *fmincon* yields only one result which is included in Table 1 as a separate column. GA results in different values presenting their optimum at the end satisfying the requirement. Table 1 presents 6 precision points on the coupler curve. Objective functions are the same with GA.

6.2. Studying the mechanism with Excel Spread Sheet

All spreadsheet programs are arranged cells as rows and columns; this depends on the requirement given by the user. Here the optimization results are taken and drawn on a spread sheet, Freudenstein's equations are utilized for the synthesis. Initial crank angles are changed successively; different solutions are found and drawn with the mechanism. It is possible to draw coupler curves and its coordinates with velocity and acceleration as well. Then they can be seen on the screen in animated sense. Some study is needed to draw mechanism in Excel. A previously prepared four bar mechanism code has been applied [30]. Fig. 4 shows the four bar mechanism. It is possible to get complete behavior of the mechanism by changing input angle.

Referring to Figure 2, the inputs are given as r1, r2, r3, r4, rcx, rcy and θ2 found from optimization. The mechanism is drawn next. If required, complete kinematic analysis can be seen as positions, velocities and accelerations for each point separately as well.

Table 1. Optimization Results for GA and (fmincon)

	Precision	Points					
	[20,20]	**[20,25]**	**[20,30]**	**[20,35]**	**[20,40]**	**[20,45]**	***fmincon***
r_1	56,338	59,97	48,01	52,64	58,90	54,34	40
r_2	54,992	55,01	53,74	59,83	57,40	54,01	50
r_3	55,369	64,89	53,87	50,62	52,06	52,20	50
r_4	54,009	59,87	59,59	57,82	50,56	51,84	60
r_{cx}	0,626	0,69	0,33	0,65	0,113	0,238	32
r_{cy}	0,306	0,33	0,82	0,69	0,206	0,669	0
Θ_2	0,652	0,39	0,52	0,18	0,746	0,498	0,524
f_{obj}	198,1	107,41	66,7	76,05	135,3	244,69	

Table 2. Target and traced points (GA)

POINTS	TARGET-X	TARGET-Y	TRACED-X	TRACED-Y
-20,20	44,011	33,351	41,874	35,997
-20,25	51,965	20,921	52,404	19,529
-20,30	43,839	32,381	41,845	35,122
-20,35	59,472	11,041	59,169	11,311
-20,40	42,753	38,602	44,131	37,07
-20,45	47,869	25,997	47,368	27,398

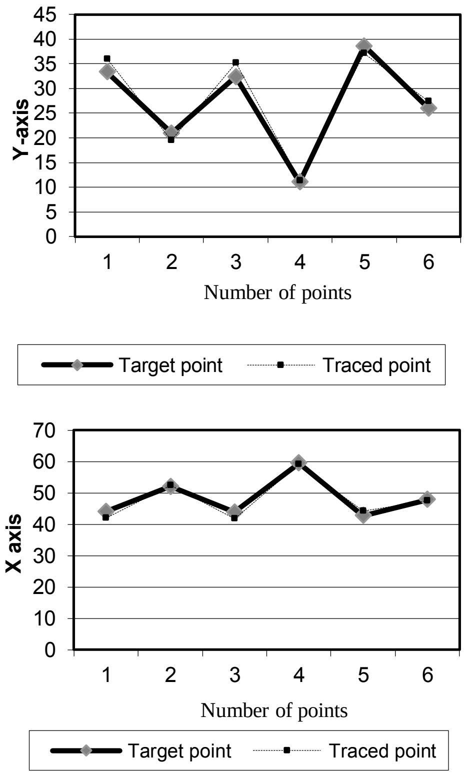
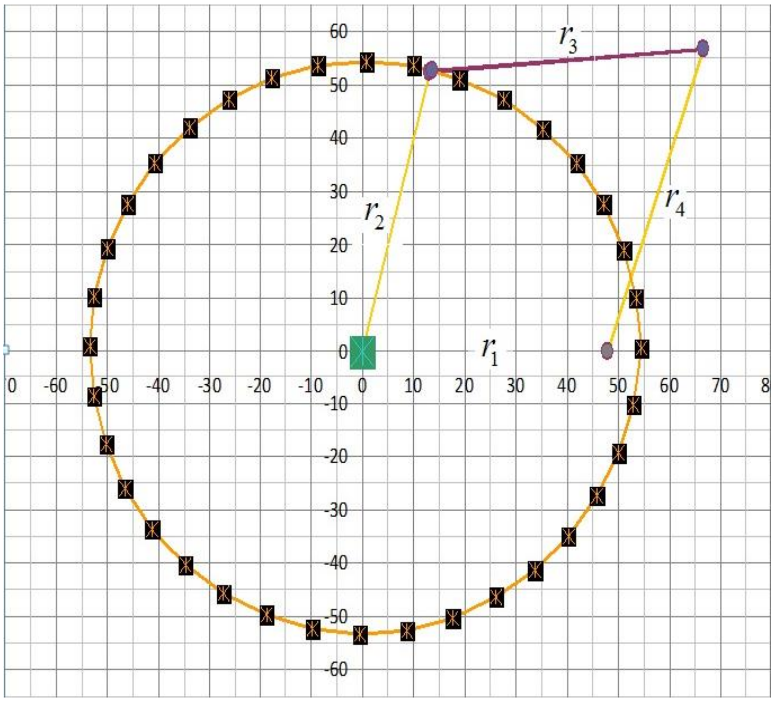


Figure 3. Target and traced points in X-Y with precision points (GA)



r_1=48.013,r_2=53.745,r_3=53.878,r_4=59.593,r_{cx}=0.332,r_{cy}=0.823

Figure 4. Four Bar Mechanism

7. Conclusion

This has presented a study for synthesis of planar mechanisms; specifically on a one degree of freedom (dof) planar mechanism. The algorithm is developed only for a Grashof's type four bar mechanism. The idea is applicable to all types of planar mechanisms. The only difference will be kinematics analysis of the mechanisms and related constraints. The main advantage seen during implementation is that of simplicity. Utilization of Optimization Toolbox is performed and a fast convergence to optimal solution is observed. Since the routine is performed directly, there will be no need for superior knowledge during optimization. It is seen that use of GA during optimization study is more advantageous to use fmincon. It presents the objective function's optimum each time. The results are similar, but not the same. (Figure 3) Therefore GA toolbox can be easily applied to mechanism synthesis problems. Only problem becomes to derive related kinematics for related mechanism as constraints [30].

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