

# High-Lift Mechanism Motion Generation Synthesis Using a Metaheuristic †

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**Abstract:** This paper proposes an approach to synthesize a high-lift mechanism (HLM) of a transportation aircraft. Such a mechanism is very important for generation of additional lift to an aircraft wing during take-off and landing. The design problem is minimization of error between the motions of a four-bar mechanism for controlling a flap to the target points. The optimum target points are positions and angles of flap at the take-off and landing conditions, which are designed based on maximizing the lift to drag ratio. Design constraints include the conditions of four-bar mechanism to work properly, limiting positions and workplace of the mechanism. A optimizer used in this study, is in a group of metaheuristics (MHs). The results show the optimum mechanism can generate flap motion fulfilling the design targets, thus, the proposed technique can be used to increase the performance of HLM.

**Keywords:** high-lift mechanism; four-bar mechanism; optimization technique; motion generation; metaheuristics

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## 1. Introduction

The high-lift system is one important part of modern large transport aircraft, which composes of flaps, a support truss, a drive mechanism, and control systems etc. The system is important for aircraft performance in both takeoff and landing [1]. The objectives for development of the high-lift system are to achieve the three objectives i.e. increasing of lift, reduction of drag, and noise reduction [2]. A transportation flap normally can have several type as plain flap, split flap, slotted flap, single-slot and double-slotted fowler flap [3], while the drive mechanisms can be a dropped-hinge, a four-bar linkage, a link-track, and a hooked-track [4]. Design methodology of the high-lift mechanism (HLM) has the aim to develop an efficient technique for mechanism synthesis.

A four-bar linkage is a common mechanism used in many machines that are included a windshield wiper, a door closer, a rock crusher, an oil well, HLM etc. Fundamental design of this mechanism is classified as function generation, path generation [5–14] and motion generation [12–14]. In this research, we adapt the previous techniques in group of the motion generation problem [12–14] to study the mechanism synthesis of HLM.

### 2. Position Analysis of Four-Bar Mechanism

A model of a four-bar linkage for HLM in this study is composed of four binary links connected with four revolute joints. A variety of linkage types are obtained when assigning anyone link to be a frame or input. The linkage has one degree of freedom, which needs only one actuator. The kinematic diagram of this linkage is shown in Figure 1. The trigonometric relations are used for position analysis of the four-bar linkage. The relation is in form of linkage lengths  $r_1, r_2, r_3,$  and  $r_4$  and other parameters, which are commonly found in standard mechanics of machinery textbooks as mentioned in [6–8]. The coupler point ( $P$ ) in the global coordinate in Figure 2 can be expressed as

$$\begin{aligned}
 x_P &= x_{O2} + r_2 \cos(\theta_2 + \theta_1) + L_1 \cos(\phi_0 + \theta_3 + \theta_1) \\
 y_P &= y_{O2} + r_2 \sin(\theta_2 + \theta_1) + L_1 \sin(\phi_0 + \theta_3 + \theta_1)
 \end{aligned}
 \tag{1}$$

where  $x_{O2}$  and  $y_{O2}$  are the coordinate positions of the joint  $O_2$  in the global coordinates [6]. The relations of the angles  $\phi_0, \theta_3, \theta_4,$  and  $\gamma$  and the link lengths  $r_1, r_2, r_3,$  and  $r_4$  at any crank angle ( $\theta_2$ ) can be found using law of cosine.

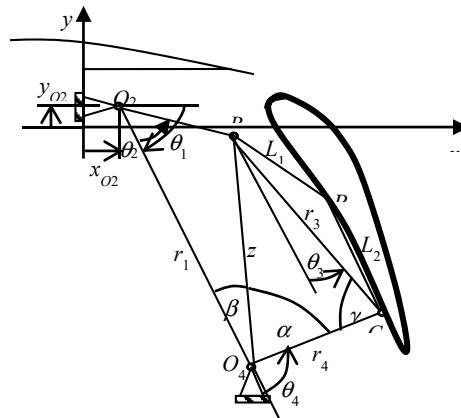


Figure 1. Four-bar linkage in the global coordinate system [1].

### 3. Optimization Problem and Constraint Handling

The objective function has two parts where the first part is the position error between the target points  $P_d(x_d, y_d)$  and the actual points  $P(x_p, y_p)$ . The second part of the objective function is in terms of the angular error between target angles ( $\theta_{3d}$ ) and actual angles ( $\theta_{3p}$ ). This research focuses only on the motion generation problem type, which is called synthesis without prescribed timing. The input set of  $\theta^i$  values is also assigned as the design variables. The optimization problem without prescribed timing is then written as:

$$\text{Min } f(x) = \sum_{i=1}^N [(x_{d,i} - x_{p,i})^2 + (y_{d,i} - y_{p,i})^2 + (\theta_{3d,i} - \theta_{3p,i})^2]
 \tag{2}$$

subject to

$$\min(r_1, r_2, r_3, r_4) = \text{crank}(r_2)
 \tag{3}$$

$$2\min(r_1, r_2, r_3, r_4) + 2 \max(r_1, r_2, r_3, r_4) < (r_1 + r_2 + r_3 + r_4)
 \tag{4}$$

$$\theta_2^1 < \theta_2^2 \dots < \theta_2^N
 \tag{5}$$

$$x_l \leq x \leq x_u
 \tag{6}$$

where  $x = \{r_1, r_2, r_3, r_4, L_1, L_2, \theta_0, x_{O2}, y_{O2}, \theta_2^i\}^T$ ,  $N$  is the number of target points, and  $x_l$  and  $x_u$  are the lower and upper bounds of the design vector  $x$ , respectively. This synthesis problem can represent the behaviour of HLM by properly applying the target points and angles.

The external penalty can be used to handle the design constraints by adding the constraints to the objective Function (2). There are two parts of the penalty function value, where the first part is assigned to control link lengths to meet the Grashof’s criterion (3)–(4). The second part is assigned to ensure the input crank can rotate with a part or complete revolution in either a clockwise or counterclockwise direction (5).

The positions of point *P* corresponding to all targets are calculated while the objective function is

$$f(x) = \sum_{i=1}^N \min d_{ij}^2 \tag{7}$$

where  $d_{ij}^2 = (x_{d,i} - x_{P,j})^2 + (y_{d,i} - y_{P,j})^2$  for  $j = 1, \dots, N$ . The details of this technique can be seen in [13,14].

In this research the desired positions and angles of HLM at both take-off and landing conditions are assigned following the previous study by Liu [2] as shown in Table 1.

**Table 1.** Desired position and angular of HLM at take-off and landing conditions.

Case	Position (xi, yi) * 1.1173	Angle, δi (°)
1. Take-off	(0.059,0.0032), (0.0642, -0.0455)	0, 24.90
2. Landing	(0.059,0.00032), (0.0703, -0.0454)	0, 43.52

From the information in the Table 1, the optimization problem can be summarized as follows.

Design variables for <b>x</b> are	Limits of the variables:
<b>x</b> = [ <i>r</i> <sub>1</sub> , <i>r</i> <sub>2</sub> , <i>r</i> <sub>3</sub> , <i>r</i> <sub>4</sub> , <i>L</i> <sub>1</sub> , <i>L</i> <sub>2</sub> , <i>x</i> <sub>o2</sub> , <i>y</i> <sub>o2</sub> , <i>θ</i> <sub>1</sub> ]	0.01 ≤ <i>r</i> <sub>1</sub> ≤ 0.3
Target points are ( <i>x</i> <sub>d</sub> , <i>y</i> <sub>d</sub> ) and <i>θ</i> <sub>3d</sub>	0.01 ≤ <i>r</i> <sub>2</sub> , <i>r</i> <sub>3</sub> , <i>r</i> <sub>4</sub> ≤ 0.5
( <i>x</i> <sub>d</sub> , <i>y</i> <sub>d</sub> ) = [(0.059, 0.0032), (0.0642, -0.0455)] * 1.1173	-0.1 ≤ <i>L</i> <sub>1</sub> , <i>L</i> <sub>2</sub> ≤ 0.2
<i>θ</i> <sub>3d</sub> = [0, 24.90] * pi/180 for case 1	<i>x</i> <sub>o2</sub> = 0
( <i>x</i> <sub>d</sub> , <i>y</i> <sub>d</sub> ) = [(0.059, 0.00032), (0.0703, -0.0454)] * 1.1173	-0.05 ≤ <i>y</i> <sub>o2</sub> ≤ 0.05
<i>θ</i> <sub>3d</sub> = [0, 43.52] * pi/180 for case 2	-60 ≤ <i>θ</i> <sub>1</sub> ≤ -45

In order to solve such a design problem, we choose a recent high-performance algorithm in solving the motion generation problem, teaching-learning based optimization (TLBO), which is coded in MATLAB commercial software. In this study the population size is set nP = 100, while the maximum number of iterations is 500. The number of running times of the algorithm is set to be 30 times to study the statistical performance of the optimizer.

#### 4. Design Results

The design result is given in Table 2. The mean objective function values from 30 optimization runs, worst result (max), the best result (min), and the standard deviation (std) are included in the table. Figures 3–6 show the best path and angle traced by the coupler point and its kinematic diagram of the best linkages. The design result of four-bar linkage synthesis for take-off condition is showed in Figures 4 and 6, while the optimum path is shown in the remaining figures. In Case-1 (Take-off condition), there are 2 target points and angles. It was found that TLBO with the traditional penalty technique gives the best result (error = 0.02297) and the mean objective value (error = 0.023221). The result of Case-2 (Landing condition) shows that TLBO with the traditional penalty technique gives the best min (error = 0.137642) and best mean (error = 0.138061). The results show that TLBO with the traditional penalty technique give moderate result in all cases due to its error are highly when comparing with the previous study with the traditional testing problems.

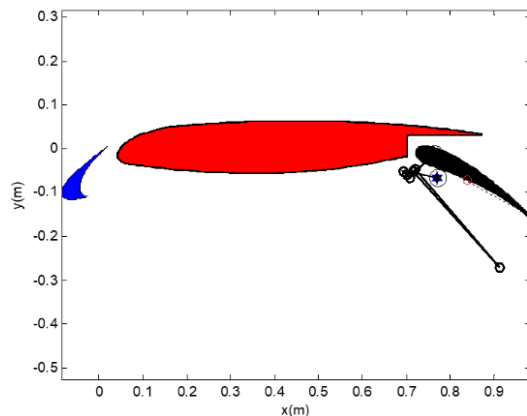


Figure 3. Optimum HLM for take-off.

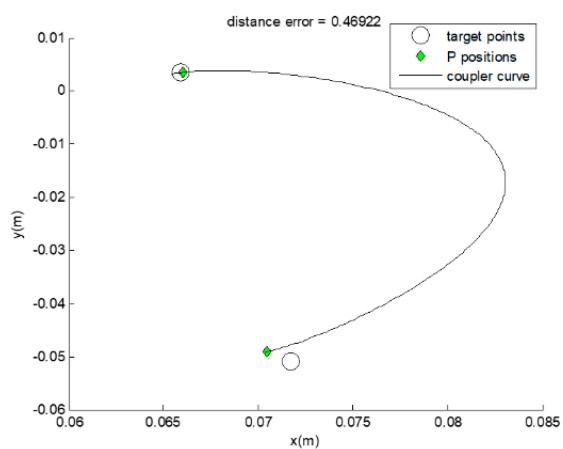


Figure 4. Optimum path of HLM for take-off.

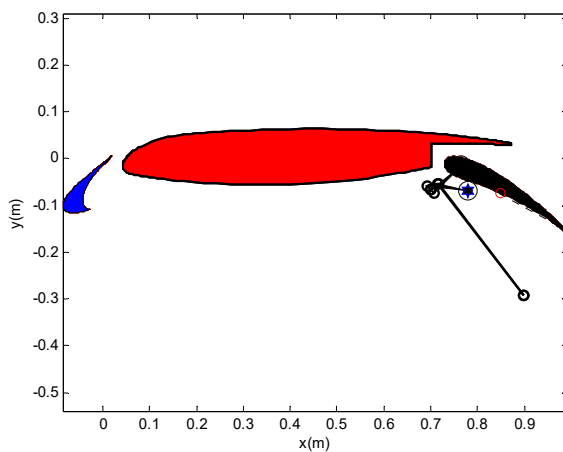


Figure 5. Optimum HLM for landing.

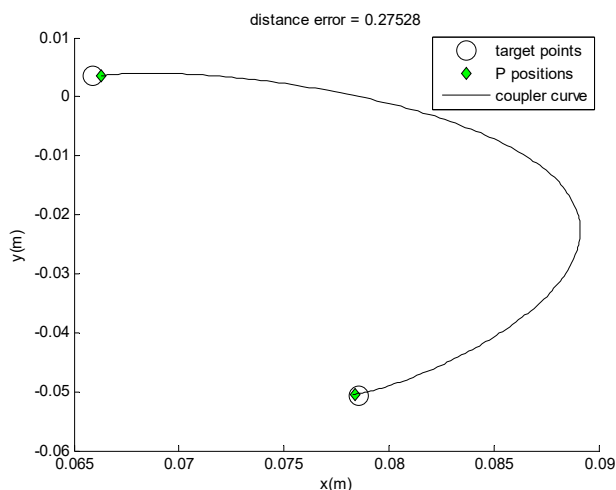


Figure 6. Optimum path of HLM of landing.

Table 2. Design results of motion generation problem.

TLBO	Parameters												
	r <sub>1</sub>	r <sub>2</sub>	r <sub>3</sub>	r <sub>4</sub>	L <sub>1</sub>	L <sub>2</sub>	x <sub>0</sub>	y <sub>0</sub>	θ <sub>i</sub>	Mean	Max	Min	std
Case-1	0.2997	0.0381	0.2192	0.3989	0.0468	0.1724	0	-0.0500	-59.9423	0.023221	0.023425	0.02297	7.21 × 10 <sup>-5</sup>
Case-2	0.2999	0.0100	0.0232	0.2993	-0.0853	-0.0637	0	-0.0500	-48.2343	0.138061	0.138456	0.137642	0.000243

### 5. Conclusions and Discussion

This paper proposed motion generation synthesis problems of the high-lift mechanism. This study is an extension of the motion generation technique in our previous study to design the high lift mechanism. Numerical experiments demonstrated that the traditional technique with TLBO can perform well, but still needs further improvement compared to the result with our previous efficient technique, which has been proved to have high performance for a motion generation problem. However, this is considered an initial study of using a traditional technique for solving the HLM motion generation problem without prescribed timing. For future work, other constraint handling techniques will be investigated.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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