Design and Dimensional Optimization of a Novel Walking Mechanism with Firefly Algorithm

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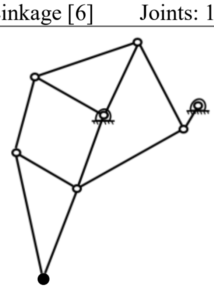
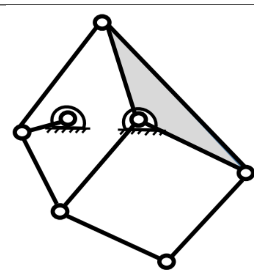
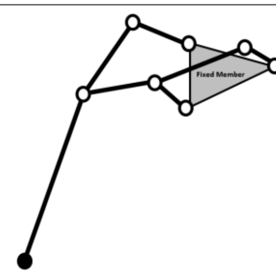
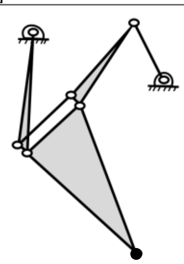
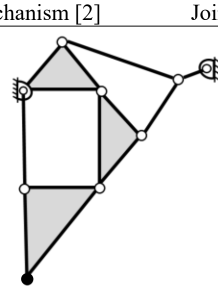
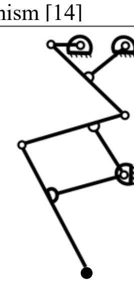
Abstract. In this paper, a walking mechanism named Atlas is proposed which is a Watt-I type 6 link mechanism. First, the geometry is proposed and then kinematic analysis is done that will be used for the synthesis problem. Furthermore, constraints and an objective function are obtained from kinematic analysis. Then, these constraints are implemented to the Firefly Algorithm and dimensional parameters are obtained for a desired step profile. Finally, these dimensional parameters are tested.

Key words: Walking Mechanisms, Kinematic Synthesis, Dimensional Optimization, Firefly Algorithm

1 Introduction

Transferring motion from one or more input to one or more output by using attached rigid members requires mechanisms. In dimensional synthesis function, motion and path generation are the solution methods [16]. For the solution of synthesis problems researchers used both analytical, numerical and graphical methods over the years [12]. In path generation synthesis problems with more than 5 points, analytical methods remain incapable. At this point, numerical methods become a part of activity to obtain mechanism dimensions with large number of desired path points. In literature, researchers usually used evolutionary algorithms to overcome synthesis problems for mechanisms. Z. Nariman et al. [12] used hybrid multi-objective genetic algorithms for Pareto optimum synthesis of four bar mechanism with minimizing two objective functions (tracking error and transmission angle error) at the same time. Lin W [21] compounded two different evolutionary algorithm named differential evolution (DE) and real-valued genetic algorithm (RGA) to synthesize four bar mechanism with several design parameters for 6, 10 and 18 points in different cases. Only considered constraints of his work were the Grashof condition, design parameters within specified ranges, rotation range of the crank and relation between input angle and crank. Acharyya S. K. and Mandal M. [1] applied three different type of evolutionary algorithm (GA, PSO and DE) to minimize the error between desired and obtained coupler curve in four bar path generation synthesis. Researcher also compared these methods between each other and selected the best one. H Yu., et al. [5] presented a computer method which uses coupler-angle function curve to synthesize a four bar mechanism. They practiced a two DoFs additional mechanism to transform coupler-points of the given path to a coupler-angle function curve. They also presented a software which give opportunity to users to define up to 20 points for path. Bulatovic R. R. and Djordjevic S. R. [15] used a direct searching method for four bar synthesis named Hooke-Jeeves's which compares its values at each iteration and changes parameters in order to described objective function. They proposed that the used algorithm in their research does not depend on the preliminary selected variables and showed a four bar example which coupler point draw a straight line. Walking mechanisms are used to simulate the walking motion of human or animals. Researchers presented various mechanisms in this area (Table 1).

Table 1. Walking Mechanisms from Literature

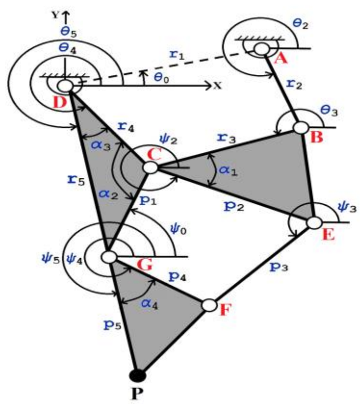
Theo-Jansen Linkage [6] — Links: 8, Joints: 10	Ghassaei [3] — Links: 7, Joints: 9	Klann Linkage [9] — Links:6, Joints:7
		
Stephenson [4] — Links:8, Joints: 10	Eight-Bar Leg Mechanism [2] — Links: 8, Joints: 7	Biped Walking Mechanism [14] — Links: 9, Joints: 6
		

The most popular walking mechanism around the world is Theo Jansen's linkage [6]. Researchers have been studied on this mechanism to optimize its link lengths [3,8] and to make its dynamic analysis[19]. Researches on Klann mechanism [9] were done in task of optimization [7] as well. For Stephenson's mechanism some researchers improved an algorithm or a method to overcome theirs synthesis problems [4, 18, 11, 23]. Al-Araidah O. et. al. [2] presented a single DoFs eight bar mechanism and synthesized it to reproduce a walking mechanism. Erika O. et. al. [14] presented and implemented a one DoF biped mechanism for a rickshaw robot which is derived from Chebshev mechanism. After building of the robot they tested the robot in different operating conditions.

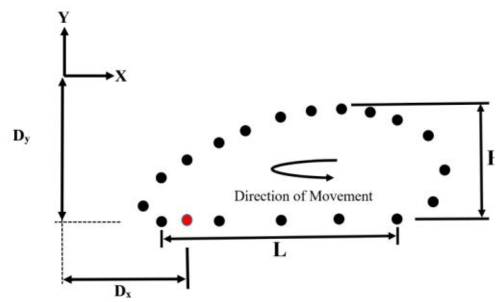
In this research, is a Watt-I type 6 link mechanism is proposed for walking. In following section, geometry of the mechanism is presented. In third section, preliminary kinematic analysis of the mechanism for synthesis is done. Forth section lays out the application of the Firefly Algorithm on this problem. Dimensional optimization of the mechanism is done in this section too. Finally, obtained dimensional parameters are tested whether they provide the desired step profile.

2 Geometry of the Walking Mechanism

The selected one DoF mechanism, which is designed to be a walking mechanism, is formed by connecting two four-bar loops (Figure 1.a). This mechanism has been chosen (Watt I type 6-link mechanism) among the mechanisms that will prove the minimum number of links by reviewing the literature. The first four-bar loop is connected to the walking body frame and its link lengths are denoted r_i, and the orientations of these links with respect to the positive X-axis are defined by the θ_i parameters. Here, mechanism is fixed to the walking body frame at joints with parameters θ_2 and θ_4, and θ_2 is selected as the input value. In mechanism, link r_2 can make full rotation. The joints with input and output parameters of the second four-bar loop are placed at the joint ends of the links r_4 and r_5. The second four-bar loop has no fixed links. The link lengths of the second four-bar loop are represented by p_i parameters and the positive X-axis orientations of these links are represent by ψ_i parameters. Stepping direction is selected as positive X-axis and gravitational acceleration is acting in the negative Y-axis direction. In mechanism, the parameters α_1, α_2, α_3 and α_4 have constant values and indicate the angle between the links r_3-p_2, r_4-p_1, r_4-r_5 and p_4-p_5 respectively. The contact point of the walking mechanism to the surface (point P) is free end of the link p_5. The reference coordinate system attached at the joint D. The presented walking mechanism is named as Atlas which has less links and joints compared to the walking mechanisms given in Table 1. Having fewer links and joints gives some advantages such as: ease of production, less energy loss during walking, less joint failures and more robustness. According to the geometry of the mechanism, this step profile can have different geometries. But a step profile always has the same components. The desired step profile for this mechanism can be seen in Figure 1.b. Here, H is the step height and L is the contact distance with the surface. D_x and D_y are the positions of the point with respect to the X-Y coordinate system attached to the walking body. Numbers of point for desired step profile are selected as 40 and these points range -70, 100 and -320, -290 respectively in X and Y coordinates.



(a)



(b)

Fig. 1 (a) Presented Walking Mechanism, (b) Desired Step Profile

3 Kinematic Analysis and Synthesis of the Mechanism

In this section, kinematic analysis of Atlas is done for both to obtain kinematic equations and to describe constraints for optimization. Before analyzing the mechanism, the relation between two four bar loops should be determined which will transfer the motion from input to output links. In the mechanism, we have a triangle link with parameters r4, r5 and p1. From cosine and sine theorem Eqs (1). are obtained.

$$p_1 = \sqrt{{r_5}^2 + {r_4}^2 - 2r_5r_4Cos(\alpha_3)},\ \alpha_2 = ArcSin\left(\frac{r_5}{p_1}Sin(\alpha_3)\right) \tag{1}$$

Second four bar loop joint angle relations with respect to first four bar loop joint expression are described in Eq. (2).

$$\theta_5 = \theta_4 - \alpha_3, \psi_2 = \theta_3 - \alpha_1 + \pi, \psi_0 = \theta_2 + \alpha_2 - 2\pi, \psi_5 = \psi_4 - \alpha_4 \qquad (2)$$

For the synthesis of walking mechanism the desired (unknown) parameters are link parameters and appropriate positions of θ_2 and known parameters are coordinate of trajectory point P as Px and Py. After relation between two four bar loops are obtained, a relation is needed to be checked whether dimensional parameters provide the desired step profile. Thus X and Y coordinates of points of the step profile are obtained in Eq. (3) by analyzing a 2-degrees-of-freedom serial kinematic chain that accept the r_5 and p_5 as link lengths and the joint at θ_4 variable as ground.

$$P_x = \mathrm{r}_5\mathrm{Cos}(\theta_5) + \mathrm{p}_5\mathrm{Cos}(\psi_5), P_y = \mathrm{r}_5\mathrm{Sin}(\theta_5) + \mathrm{p}_5\mathrm{Sin}(\psi_5) \qquad (3)$$

Now, we need to obtain equations for θ_5 and ψ_5 to use them later both as constraints for optimization algorithm and to determine the error. After that two function generation problems will be defined for θ_4 and ψ_4 from θ_5 and ψ_5. Here θ_2 and θ_4 are our input and output values for first, ψ_2 and ψ_4 for second loop respectively. Let's consider we have a 2 degrees of freedom serial manipulator with parameters r_5 and p_5 and joint variables θ_5 and ψ_5 can be computed from Eq. (3). When, loop clousure equation is written for the first and second four bar loops, we have the following equations.

$$\vec{r}_1 + \vec{r}_2 + \vec{r}_3 = \vec{r}_4,\ \vec{p}_1 + \vec{p}_2 + \vec{p}_3 = \vec{p}_4 \qquad (4)$$

After rewriting Eq. (4) and (5) explicitly, θ_4 and ψ_4 can be drawn from these equations.

4 Optimization of Dimensional Parameters

To obtain dimensional parameters for walking mechanism Firefly Algorithm is used. First of all constraints and objective function should be determined for optimization. Constraints for Firefly Algorithm are defined as follows. The Grashof conditions should satisfy full rotation for input link of the first four bar loop. For second four bar loop, there is no need of full rotation. Link lengths relations for Grashof condition are given in Eq. (6). Link lengths are defined within the specified ranges. All link lengths parameters are expected to be between 10 mm and 400 mm. Also, situations which would make the $\theta_4, \theta_5, \psi_4$ and ψ_5 equations undefined or imaginary are added as constraints. Objective function is chosen as a maximization problem. To minimize the error of path the dimensional parameters of the designed walking mechanism are aimed to be synthesized by using Firefly Algorithm. Firefly algorithm is developed by Yang [22] and is a nature inspired metaheuristic algorithm [13]. In firefly algorithm, each agents (fireflies) propagate lights and brighter ones pull other fireflies in close [10]. Few researchers in robotics used firefly algorithm to overcome optimization problem for their mechanisms. Nedic N. et. al. [17] proposed a cascade load force control design for a parallel robot platform. They used Firefly algorithm for parameter searching. Also they indicate that firefly algorithm is very effective in nonlinear optimization tasks and performs better than other metaheuristic algorithms. They performed four different nature inspired algorithms (GA, PSO, CS and FA) on five different tasks. Researchers have procured that Firefly Algorithm is independent from the complexity of problems, has a better rate of convergence and gives values faster than other tested algorithms. One major reason for choosing Firefly Algorithm is that it can solve highly nonlinear, multimodal problems with high efficiency. Saputra V.B. [10] used firefly algorithm for determination of parallel manipulator's workspaces. From outline derived by Yang X. S. [13], firefly algorithm was applied to our optimization problem as shown in Table 2.

$$r_1 + r_3 - r_2 - r_4 < 0 \; V \; r_4 + r_1 - r_2 - r_3 < 0 \; V \; r_4 + r_3 - r_2 - r_1 < 0 \tag{5}$$

Table 2. Applied Firefly Algorithm for Dimensional Optimization of Atlas

Objective function $f(\boldsymbol{x}_i)$,
$\boldsymbol{x}_i = \left(r_1, r_2, r_3, r_4, r_5, p_1, p_2, p_3, p_4, p_5, \theta_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \theta_{2,i}\right)^T$, where
$f(\boldsymbol{x}_i) = 1/(1 + Sum\ [(Error_1 + Error_2), (i, 1, n)])$
Generate initial population of fireflies $\boldsymbol{x}_i(i = 1,2, \dots, n_f)$.
Light intensity I at $\boldsymbol{x}_i$ is determined by $f(\boldsymbol{x}_i)$
Define light absorption coefficient γ
for $(m_i; 1, MaxGen)$
  for $i = 1{:}\,n_f$
    for $j = 1{:}\,n_f$
if $(I_i < I_j)$,
  $r_{i,j} = \sqrt{Sum\left[\left(x_{k,i} - x_{k,j}\right)^2, (k, 1, n_c)\right]}$;
  Do$\left[x_{k,i} = x_{k,i} + \frac{\beta_0}{1+\gamma\, r_{i,j}^2}\left(x_{k,j} - x_{k,i}\right) + \alpha\ (Random[\,] - 0.5), \{k, 1, n_c\}\right]$, (move firefly i towards to j)
  else Do$\left[x_{k,i} = x_{k,i} + \alpha\ (Random[\,] - 0.5), \{k, 1, n_c\}\right]$, (move firefly random)
end if
Evaluate new solutions of $f(\boldsymbol{x}_i)$ and update light intensity
    end for j
  end for i
Rank the fireflies and find the current global best **g***
end for

Parameters used in the algorithm were selected by taking into consideration of Lukasik S. and Zak S.'s research about firefly algorithm [10]. In algorithm which was given in Table 2, n_f denotes the population of fireflies and is selected 25 and n_c is the number of coordinates and signs the number of variables which are expected to be optimized (We have 16 variables to be optimized). γ is called approach speed or absorption coefficient and it states multifariousness with escalating distance from interacted firefly [10] and is selected as 0.1. β_0 is the attractiveness, it indicates the capability of a firefly to draw in other fireflies and is selected as 0.8. α is defined as randomness and it remarks the how much fireflies move randomly and is selected as 0.1. Light intensity of a firefly is measured by I and it directly impresses the movement of fireflies. Here $f(\boldsymbol{x}_i)$ is the objective function and $\boldsymbol{x}_i$ is the solution for parameters which are wanted to be optimized at each iteration. Finally $r_{i,j}$ is the monotonically decreasing function of the distance between fireflies. As the error decreases and approaches zero, the objective function value approaches the maximum value one. The straight line which is followed by the end point of the Atlas has major importancy then the arc part of the step profile. Error weight (w_n) for straight line and arc part are taken as 1 and 0.4 respectively in objective function. $Error_1$ and $Error_2$ in objective function are expressed as follow.

$$Error_1 = \sum_{i=1}^{n} w_n |\theta_{4r,i} - \theta_{4c,i}|, Error_2 = \sum_{i=1}^{n} w_n |\psi_{4r,i} - \psi_{4c,i}| \tag{6}$$

Where n is the number of points , θ_{4r} and ψ_{4r} are the desired output values and θ_{4c} and ψ_{4c} are the obtained output values from Firefly algorithm.

5 Testing of Obtained Parameters

Because of error weight for straigh line 1 and arc part 0.4 objective function value comes around 0.6 which also one can be seen from Figure 2. Obtained step profiles are suitable for a walking mechanism. Value of the objective function can be 1 without error. Firefly Algorithm gave the best value between 0.52 and 0.62 with 5000 iterations. Also, Atlas's geometry gives us one more advantage that reaction forces from ground are faced by links r_5 and p_5 nearly in perpendicular direction relative to surface.

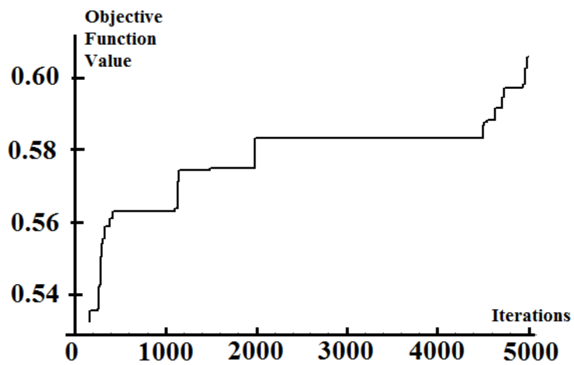


Fig. 2 Objective Function Value for 5000 Iterations

Dimensional parameters are obtained after 5000 iterations from Firefly Algorithm One also is given that the model of the walking mechanism with dimensional parameters (Figure 3). In this section, it was checked whether the obtained optimum dimensional parameters provided the desired step profile. When we substitute these dimensional parameters into first θ_4, ψ_4, then θ_5, ψ_5 and finally into Eq. (3) we get the step profile for the mechanism. The step size of the found mechanism is desired as 170 mm in x direction, mechanism size become 200 mm in x direction. The ratio of time taken on ground to the time taken above the ground is found around 0.8 even though it is important for the conversation of potential energy in walking mechanisms the ratio is not considered in this study.

All units for link lengths are mm, for angles are radian.

r_1=	160.7	p_1=	78.4	α_1=	1.3
r_2=	41.5	p_2=	132.8	α_2=	1.5
r_3=	140.9	p_3=	94.3	α_3=	0.7
r_4=	86.3	p_4=	110.3	α_4=	6.9
r_5=	121	p_5=	209.5	θ_0=	6.3

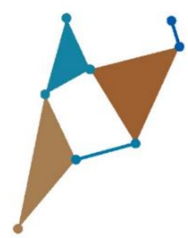


Fig. 3 Presented Walking Mechanism with Optimized Dimensional Parameters

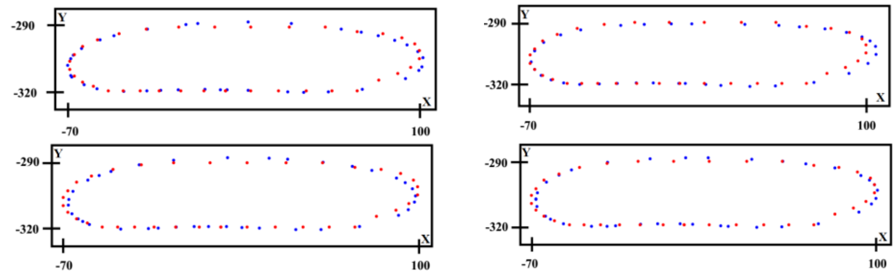


Fig. 4 Desired and Obtained Step Profiles (units are mm) (Red and blue dots indicate the desired and obtained step profiles respectively.)

6 Conclusion

In this research, a walking mechanism with one DoF named Atlas is presented. Firstly, its dimensional parameters and geometry are shown. A step profile that will be followed by the end point of the walking mechanism is proposed. Inverse kinematic equations of the walking mechanism are extracted to be used as constraints for Firefly Algorithm. Algorithm is run to get the optimized dimensional parameters to provide the desired step profile. After 5000 iterations dimensional parameters are obtained. These parameters are checked to test whether mechanism with optimized dimensional parameters provide the desired step profile. Test results show that obtained step profile is coinciding with the desired one with a straight line. For future works, it is aimed to implement this legs into a rescue robot.

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