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# Design of a Single Actuator Walking Robot via Mechanism Synthesis Based on Genetic Algorithms

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## Abstract

In the past decades, an extensive research has been focused on legged walking robots. One of the most attractive trends in the design of walking robots is the development of biped robots with reduced number of degrees of freedom. This paper deals with a new solution of a legged walking mechanism with four-bar mechanism and only one actuator. A Genetic algorithm based mechanism synthesis has been implemented in the design of four-bar mechanism. The efficiency of the suggested design of the legged walking robot is illustrated by numerical simulations that carried out via ADAMS, and the results show that this design has the capability of walking both forward and backward.

**Keywords:** Mechanism design, Four-bar linkage, Walking robot, Mechanism synthesis, Genetic algorithm.

## Introduction

It is well known that legged locomotion is more efficient, speedy, and versatile than one by track and wheeled vehicles when it operates on a rough terrain, steeps stairs or avoid obstacles. This research field has attracted great interest of many research groups and companies in the past few decades.

The pioneering works in the field of legged robots were achieved around 1970 by two famous researchers, Ichiro Kato [1-3] and MiomirVukobratovic [4,5]. Both works were characterized by the design of relevant experimental systems. In Japan, the first anthropomorphic robot, WABOT 1, was demonstrated in 1973 at Waseda University. In Yugoslavia, Belgrade, at the MihailoPuppin Institute, MiomirVukobratovic and his team designed the first active exoskeletons and several other devices. The end of the millennium was a period of intense technological activities. Industrial breakthroughs showed to the world that building true humanoids was now possible. In Japan, the first humanoid robot "P2" was exhibited by Honda in 1996, followed by several more:ASIMO (Honda), QRIO (Sony), HRP (Kawada), etc.

To create biped robots walking like a human is necessary to use a large number of actuators. Therefore, these robots are automorphic and flexible. However, there are several drawbacks: complexities of the design and the control system, low energy efficiency due to the masses of motors, as well as an overly high price complicating practical use. Hence, in order to make a biped robot more attractive, a different methodology can be considered such as constructing a biped robot with reduced number of degrees of freedom [6-9]. In the last decade, at the Laboratory of Robotics and Mechatronics in Cassino University, Marco Ceccarelli and his team have proposed various solutions for Low-Cost Easy-Operation leg design [10]. The Chebichev four-bar linkage has been successively used for generation a foot trajectory. In order to amplify the produced motion of the Chebyshev linkage, a pantograph mechanism has been utilized. In other studies [11-13], five-bar mechanism, Klann Mechanism and Jansen Mechanism have been adopted for the design of walking robots with reduced number of actuators.

The four-bar mechanism is one of the simplest but practically widespread mechanisms. It has been used in various industrial fields, such as automatic door-closing systems, train suspensions, front loader mechanisms, etc. In order to adopt the four-bar mechanism into different engineering fields, many researchers [14-17] have conducted researches on the graphical and analytical methods of the design of four-bar mechanism. However, these methods are often with low precision and will increase the computational time and complexity when the prescribed points increased [18]. In the last three decades, with the significantly development of the computer industry, the computational ability of computer has been greatly increased which allow researchers via numerical methods to solve sophisticated optimization problems. Among these numerical methods, genetic algorithm (GA) [19-21]has been widely used among researches from various fields as one of the most effective approaches to solve non-linear optimization problems. Recently, several researchers have implement GA in the design of four-bar mechanism. J.A Cabrera et al. from University of Malaga applied GA to design the four-bar mechanism [22]. In their research, they used the difference between desired points and actual points as the goal function to be minimized and several constraints had been set such as Grashof condition and sequence condition. Based on this research, N. Nariman-Zadeh et al. from University of Guilan introduced the Pareto optimum synthesis, and the influences of transmission angle and maximum angular velocity ratio of four-bar mechanism were concerned [23].

This paper is organized as follows. In the first section the optimization method is discussed. Then, optimal synthesis of four-bar mechanism is considered. After, the design of one-degree of freedom walking robot is shown. Finally, the results of numerical simulations are presented.

## Optimization method

Genetic algorithm (GA) is a kind of mathematical algorithm which is inspired by the process of natural selection. Nowadays, GA is widely and commonly used for solving multi-parameter optimization problems.

In GA, a population of candidate solutions (individuals) to an optimization problem is evolved toward better solutions. Like the creature, each individual has a set of properties (chromosomes) which can be mutated and altered.

Normally, the GA starts from a population of individuals which are randomly generated, and the population in each iteration is called a generation. In each generation, there is an objective function to evaluate the fitness of each individual in the population. The more fit individuals are stochastically selected from the current population, and each individual's genome is modified (recombined and mutated) to form a new generation. The new generation of candidate solutions is then used in the next iteration of the algorithm. Commonly, when the maximum number of generation is or a satisfactory fitness level is reached, the GA will be terminated. The general procedure of GA is shown in Figure1.

The selection procedure chooses parents for the next generation based on their fitness values. During each successive generation, a portion of the existing population is selected to breed a new generation. Certain selection methods rate the fitness of each solution and preferentially select the best solutions. Other methods rate only a random sample of the population, as the former process may be very time-consuming.

In the present study, we use the stochastic uniform method in the selection procedure. It lays out a line in which each parent corresponds to a section of the line of length proportional to its expectation. The algorithm moves along the line in steps of equal size, one step for each parent. At each step, the algorithm allocates a parent from the section it lands on. The first step is a uniform random number less than the step size.

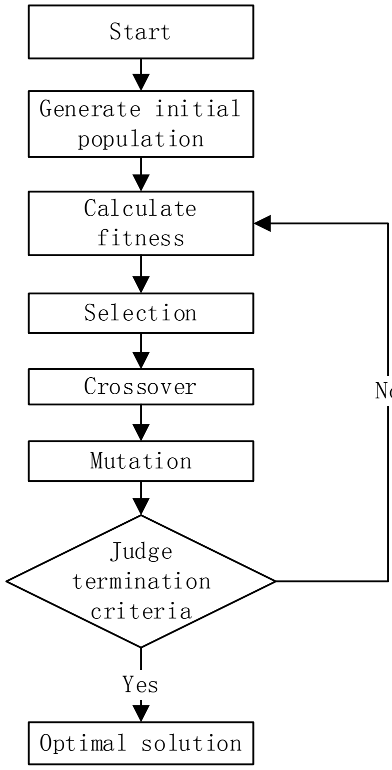


**Figure 1:** General procedure of GA

In GA, crossover is a genetic operator used to vary the programming of a chromosome or chromosomes from one generation to the next. It is analogous to reproduction and biological crossover, upon which genetic algorithms are based. Cross over is a process of taking more than one parent solutions and producing a child solution from them. There are methods for selection of the chromosomes (i.e. Scattered, Single point, Intermediate).

Scattered has been used in the Crossover process of the present study. Scattered creates a random binary vector. It then selects the genes where the vector is a 1 from the first parent, and the genes where the vector is a 0 from the second parent, and combines the genes to form the child. This method can be shown as

$$\begin{aligned} p_1 &= [a\ b\ c\ d\ e\ f\ g\ h] \\ p_2 &= [1\ 2\ 3\ 4\ 5\ 6\ 7\ 8] \\ \textit{random crossover vector} &= [1\ 1\ 0\ 0\ 1\ 0\ 0\ 0] \\ \textit{child} &= [a\ b\ 3\ 4\ e\ 6\ 7\ 8] \end{aligned} \tag{1}$$

Mutation is a genetic operator used to maintain genetic diversity from one generation to the next. It is analogous to biological mutation. Mutation alters one or more gene values in a chromosome from its initial state. In mutation, the solution may change entirely from the previous solution. Hence GA can come to better solution by using mutation. Mutation occurs during evolution according to a user-definable mutation probability. This probability should be set low. If it is set too high, the search will turn into a primitive random search.

There are several algorithms for Mutation in GA, for example, Gaussian, Uniform, and Adaptive feasible. In the present study, the Adaptive feasible has been used in the Mutation procedure. It randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation. A step length is chosen along each direction so that linear constraints and bounds are satisfied.

Leg design via synthesis of four-bar mechanism with prescribed path trajectory

To adapt the GA to the path-generation based optimal synthesis of four-bar mechanism (Figure 2), the goal function in the GA must be defined at first.

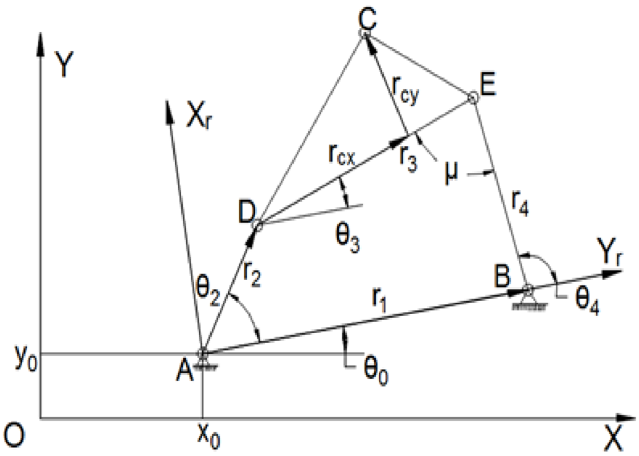


**Figure 2:** A planar four-bar mechanism with design parameters

The ultimate goal of the path-generation based optimal synthesis is to optimize a four-bar mechanism which can generation a path (the trajectory of point C in Figure 2) as close as possible to the prescribed points (also known as design points). Hence, the first part of the goal function is the difference between actual points and design points, which can be expressed by:

$$\sum_{i=1}^{N}\left[(C_{Xd}^{i}-C_{X}^{i})^{2}-(C_{Yd}^{i}-C_{Y}^{i})^{2}\right] \tag{2}$$

where $N$ is the number of design points, $C_i$=[*C i X, C i Y*]=[$C_X$(*θ i 2), $C_Y$(θ i 2)*]is the coordinates of actual path points of the optimized four-bar mechanism, *Ci d*=[*CiXd, CiYd*] is the coordinates of the design points.

In the optimal synthesis, the design variables are $r_1$, $r_2$, $r_3$, $r_4$, $r_{cx}$, $r_{cy}$, $\theta_0$, $x_0$, $y_0$, and input angle $\theta_2$ as shown in Figure 2. However, to calculate the coordinates of actual points $C_i$, the value of $\theta_3$ must be solved first. In order to calculate $\theta_3$, the closed equation of four-bar mechanism has been introduced:

$$\begin{cases} r_2\sin\theta_2+r_3\sin\theta_3=r_4\sin\theta_4 \\ r_2\cos\theta_2+r_3\cos\theta_3=r_1+r_4\cos\theta_4 \end{cases} \tag{3}$$

It can be rewritten as:

$$\begin{cases} \cos\theta_4=(r_2\cos\theta_2+r_3\cos\theta_3-r_1)/r_4 \\ \sin\theta_4=(r_2\sin\theta_2+r_3\sin\theta_3)/r_4 \end{cases} \tag{4}$$

By squaring both the equations of Eq. 4 and adding them together, we can obtain a quadratic equation with respect to $cos\theta_3$. And the solution can be represented as flowing:

$$\cos\theta_3=\frac{AB}{D^2}\pm\left[\left(\frac{AB}{D^2}\right)^2-\frac{B^2-C^2}{D^2}\right]^{1/2} \tag{5}$$

where:

$A=2r_3(r_2cos\theta_2-r_1)$

*B=r2 4-r2 1-r2 2-r2 3+2*$r_1r_2cos\theta_2$

$C=2r_2r_3sin\theta_2$

$D=(A^2+C^2)^{1/2}$

then$\theta_3$ and $\theta_4$ can be easily calculated:

$$\begin{gathered}\theta_3=\arccos\left\{\frac{AB}{D^2}\pm\left[\left(\frac{AB}{D^2}\right)^2-\frac{B^2-C^2}{D^2}\right]^{1/2}\right\} \\ \theta_4=\arccos\left[(r_2\cos\theta_2+r_3\cos\theta_3-r_1)/r_4\right]\end{gathered} \tag{6}$$

Thus, the position of point *C* in the local reference $O_2X_rY_r$, which has been defined in Figure 2, is:

$$\begin{gathered} C_{Xr}=r_2\cos\theta_2+r_{cx}\cos\theta_3-r_{cy}\sin\theta_3 \\ C_{Yr}=r_2\sin\theta_2+r_{cx}\sin\theta_3+r_{cy}\cos\theta_3 \end{gathered} \tag{7}$$

and it can be transferred to the global coordinate in reference *OXY*:

$$\begin{bmatrix} C_X \\ C_Y \end{bmatrix}=\begin{bmatrix} \cos\theta_0 & -\sin\theta_0 \\ \sin\theta_0 & \cos\theta_0 \end{bmatrix}\begin{bmatrix} C_{Xr} \\ C_{Yr} \end{bmatrix}+\begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \tag{8}$$

The first part of goal function can be calculated from Eq. 2.

In order to obtain a desirable four-bar mechanism, there are several constraints which have to be complied. For example, the Grashof condition which allows at least one link has the entire rotation, sequence condition of input angle $\theta_2$ which guarantee the continuity of input angles, and the limitation of design variables. Therefore, in the second part of the goal function, these constraints have been introduced. Now, the synthesis conditions can be described as follows:

$$\min\left\{\sum_{i=1}^{N}\left[(C_{Xd}^{i}(X)-C_{X}^{i}(X))^{2}+(C_{Yd}^{i}(X)-C_{Y}^{i}(X))^{2}\right]\right\}$$

subject to:

(a) Grashof condition: $2(r_{max}+r_{min})<(r_1+r_2+r_3+r_4)$

(b) Sequence condition: θ *j 2*<θ*mod(j+1,N) 2*<…<θ*mod(j+N,N) 2*

(c) Limitation of design variables: $x_i\in[L_i^l,L_i^u]\forall x_i\in X$

where $r_{max}$ is the length of the longest linkage, $r_{min}$ is the length of the shortest linkage, θ *i 2* is the value of $\theta_2$ in its *ith* position, θ *j 2*=min{θ *i 2*}, *X* is the set of all design variables, *Ll i* and *Lu i* are the lower and upper limitation of *ith* design variable.

In GA, the limitation of design variables can be prescribed. With the addition of the penalty of the constraints, the entire goal function can be written as:

$$\min\left\{\sum_{i=1}^{N}\left[(C_{Xd}^{i}(X)-C_{X}^{i}(X))^{2}+(C_{Yd}^{i}(X)-C_{Y}^{i}(X))^{2}\right]+P_1 f_1(X)+P_2 f_2(X)\right\} \tag{9}$$

where$f_1(X)=0$ when Grashof condition is satisfied

$f_1(X)=1$ when Grashof condition is not satisfied

$f_2(X)=0$ when Sequence condition is satisfied

$f_2(X)=1$ when Sequence condition is not satisfied

and $P_1$ and $P_2$ are the penalty coefficients of Grash of and Sequence condition, which are usually set to a high value in order to have suitable results.

## Design of the single-actuated walking robot

The typical walk consists of a repeated gait cycle. The cycle itself contains two phases: a propelling phase and non-propelling phase [10]. In Figure 3, the thicker line represents the supporting leg (right leg) in propelling phase and the thin line represents the swing leg (left leg) in non-propelling phase. It is known that for design a one-degree of freedom leg mechanism with back-forth and up-down motion capability, the foot point should generate an ovoid curve, which is composed of a straight-line segment and a curved segment (see Figure 1). The straight-line segment is related to the propelling phase when the corresponding leg touches the ground and could guarantee stable propelling of the body. The curved segment is related to the non-propelling phase, which is produced by leg when it swings from back to forth.

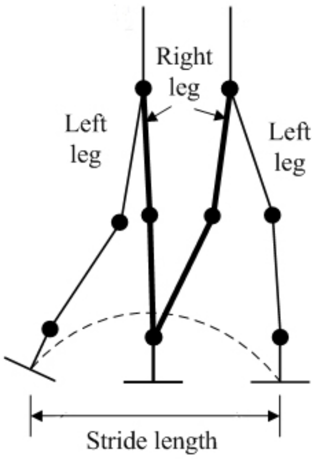


**Figure 3:** Two-stage step cycle for human walking gait

However, the use of multiple actuators increases not only the whole weight of the robot which makes the robot very bulky, but also the complexity of the control system. In order to tackle this drawback, many researches [9-13,24-26] have been conducted focus on the design of walking robot with reduced number of degrees of freedom.

In the present paper, the four-bar linkage is used as a leg of a walking robot. The four-bar mechanism has the capability to generate different types of trajectory. However, to design a four-bar mechanism which can generate humanoid walking step is often intractable because in human step, there has both straight segment and curved segment. But with the optimal synthesis which has been discussed in the third section, the four-bar mechanism allows one to generate the straight segment and curved segment of the mentioned trajectory.

In the present study, Matlab and its GA toolbox have been used for the implementation of the method described in Section 3. The general setting of the problem is showed by Table1. During the optimization, the best fitness values with respect to the generation are shown in Figure 4. The optimization satisfied the stopping criteria at 50$^{th}$ generation with a final error of 0.02935 and the best optimized parameters are: $r_1$= 34.38101; $r_2$= 12.45077; $r_3$= 33.18885; $r_4$= 40.84949;$r_{cx}$=14.65532; $r_{cy}$=34.19804; $\theta_0$=0.24857; $x_0$=44.95475; $y_0$=25.73308; θ*1 2*=5.80584; θ*2 2*=6.20891; θ*3 2*=0.22071; θ*4 2*=0.52381; θ*5 2*=0.94945; θ*6 2*=3.48114.

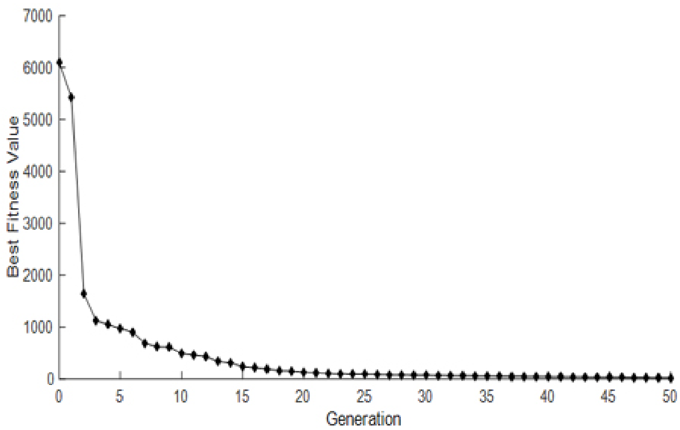


**Figure 4:** Best fitness values with respect to the generation

Figure 5 shows the comparison of the trajectory generated by the designed mechanism and prescribed points. As we can see, this is a very desirable trajectory for design a walking robot. Figure 6 shows the change transmission angle of the optimal mechanism with the rotation of input bar. It can be seen that the optimal mechanism is a proper design sine the transmission angles are between 35° and 80°.

After obtaining the parameters of the optimal four-bar mechanism, the design the walking robot can be carried out. Figure 7 shows the relationship between input bar motion and leg trajectory, the thick and thin solid lines below represent the leg trajectory in stand and swing phase respectively; the input link motion with respect to the stand and swing phase is represented by the above thick and thin dot lines respectively. It can be seen that the input link motion with respect to the stand and swing phase are equally divided and the difference of the angles of input bar between two legs is always 180°, hence the left and right leg can be driven by a single actuator. The CAD model of the suggested walking robot was built by using dynamics simulation software ADAMS (Figure 8). It should be noted that two “feets” are connected at the output points of the four-bar mechanisms by torsion springs and dampers which maintain the balance of the robot during walking.

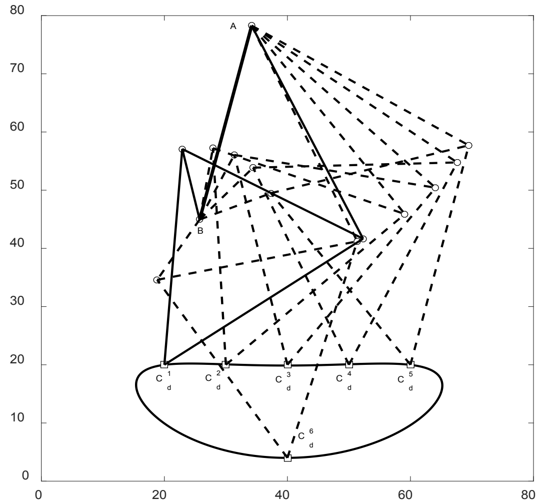

**Figure 5:** Comparison of the optimal mechanism's trajectory and design points

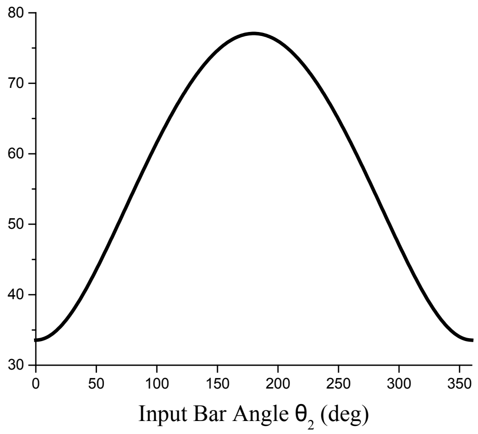


**Figure 6:** Change of transmission angle with respect to the input bar angle

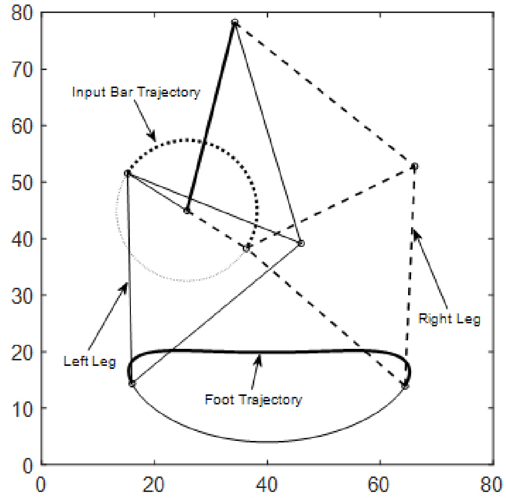


**Figure 7:** Leg trajectory with respect to the motion of input link

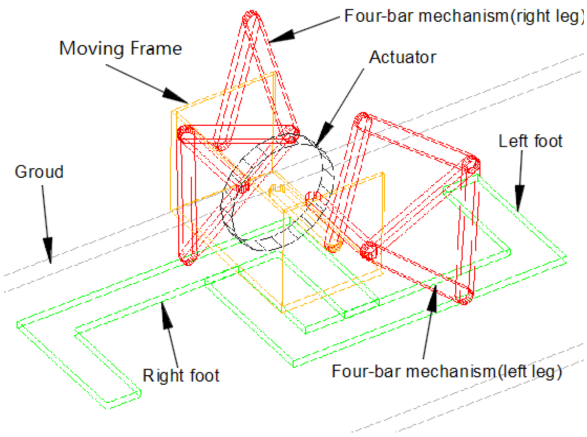


**Figure 8:** CAD model of the walking robot

## Simulation results

To verify whether the robot which designed in previous section has the capability of walking, a simulation was conducted by using ADAMS.

In order to simulate the proposed design in both different speeds and different walking directions, there different rotational speeds of actuator have been set, which are 60°/s, 120°/s, -60°/s respectively. The total simulation time of each simulation is 30s.

Figure 9 and Figure 10 show the snapshots of part of the motion of the walking robot during simulation when it's walking forward and backward with the speeds of actuator of 60°/s and -60°/s respectively. The simulation verified that the robot has the ability of both walking forward and backward. The displacements of the mass centre of robot's moving frame along walking direction with different actuator speeds are shown in Figure 11. As we can see from these two figures, the robot was walking at a constant speed with both low and high speeds and different walking directions.

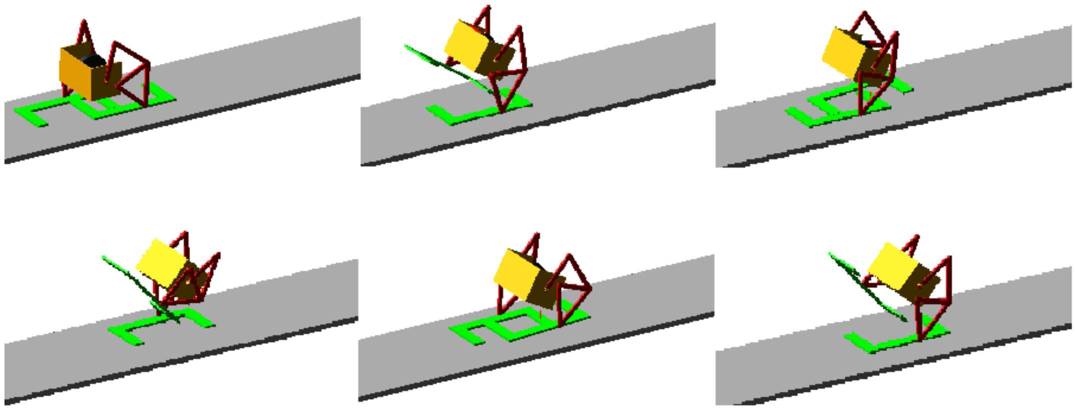

**Figure 10:** Snapshots of the simulation when robot moving backward (-60°/s)

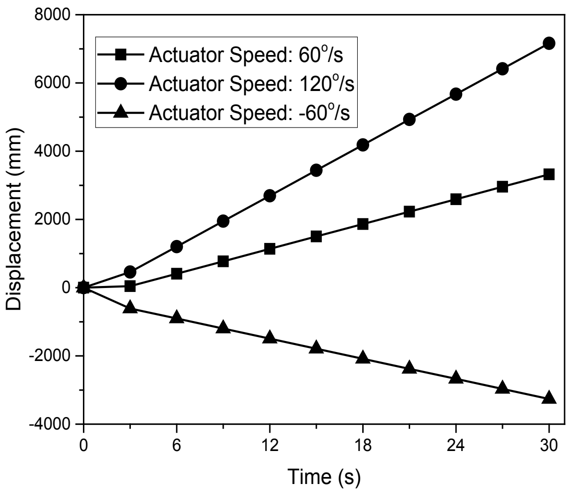


**Figure 11:** Displacements of the mass centre of robot's moving frame along walking direction with different walking speeds

## Conclusion

This paper deals with the design of a walking robot with reduced degree of freedom. A four-bar mechanism has been used as the leg of this walking robot. In the first part of the study, a mechanism synthesis based on the Genetic Algorithm has been developed. It proposed geometric synthesis of the four-bar linkage allows one to find the lengths of links that ensure the reproduction of prescribed points of the given trajectory. The suggested walking robot consist of a moving frame connected with two synthesized four-bar linkages. The actuator of the walking robot is mounted at the centre of its moving frame and moves both legs. To validate the performance of the walking robot, a simulation has been carried out via ADAMS. The obtained results showed that the robot is capable to walk steadily both forward and backward at different constant speeds.

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