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Hexapod Robot Static Stability Enhancement using Genetic Algorithm

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Abstract

Hexapod robot is a flexible mechanical robot with six legs. It has the ability to walk over terrain. The hexapod robot look likes the insect so it has the same gaits. These gaits are tripod, wave and ripple gaits. Hexapod robot needs to stay statically stable at all the times during each gait in order not to fall with three or more legs continuously contacts with the ground. The safety static stability walking is called (the stability margin). In this paper, the forward and inverse kinematics are derived for each hexapod's leg in order to simulate the hexapod robot model walking using MATLAB R2010a for all gaits and the geometry in order to derive the equations of the sub-constraint workspaces for each hexapod's leg. They are defined as the sub-constraint workspaces volumes when the legs are moving without collision with each other and they are useful to keep the legs stable from falling during each gait. A smooth gait was analyzed and enhanced for each hexapod's leg in two phases, stance phase and swing phase. The proposed work focused on the two approaches first, the modified classical stability margins. In this approach, the range of stability margins is evaluated for all gaits. The second method is called stability margins using Genetic Algorithm (GA) that enhanced the static stability by getting the best stability margins for hexapod robot and these results are useful to get best stable path planning of hexapod robot with smaller error than the first approach and with better new stable coordinates of legs tips than the first method. In addition, the second approach is useful for getting the better new stable center body coordinates than center body coordinates in the first approach of hexapod robot.

Keywords: *Kinematics, Stability Margin, Workspace, Genetic Algorithm and Hexapod Robot.*

1. Introduction

The hexapod robots are mechanical vehicles that walk with six legs; they have attracted considerable attention in recent decades. There are several benefits for hexapods rover such as: efficient one to maintain for statically stable static on three or more legs, it has a great deal of flexibility in how it can move [1]. There is a difficult problem of generation and control of the sequences of placing and lifting legs such that at any instant body should be stable and moving from one position to other. The gait is defined as generation and sequences of legs during the hexapod motion [2]. Hexapod robot looks like insect so it has the same gaits [1]. The three gaits of hexapod are: Wave, Ripple, and Tripod gait [3]. The GA is determined the optimal movement by the hexapod leg for walking robot with three degrees of freedom, with higher positioning precision By using an Analytical Hierarchy Process [4]. The stability of hexapod is a main problem to maintain it from fall during its walking with using the (GA) in order to get the optimal movement. Hexapod simulation with a (GA) are used to determine the robot's movements for generating chromosomes which are created from a repeated sequence of static leg positions, the fitness function equation using the main factor stability and efficiency [5]. The objective function is used as the stability margin to find optimal walking gaits for an 8-legged robot as in [6].

In this paper the main problem is when hexapod robot walking and may be fall down if the legs are not constraints so the two approaches are analyzed, one that called the modified classical stability margins is depended on according to constraints of each leg in order not to fall and the other approach is called stability margins enhancement using Genetic Algorithm is based on the stable ranges values that getting from first approach. The Genetic Algorithm is used to get the best stability margins and these results are useful to get best stable path planning of hexapod robot.

2. Modeling of Hexapod Robot

The legged locomotion verities by verity of usual terrain and it presents a set of difficult problems (foot placement, obstacle avoidance, load distribution, common stability) which must be taken into account both in mechanical construction of vehicles and in development of control strategies [7]. Besides that, these issues are using models that mathematically explain the verities of situations and for that; the robot modeling becomes a practical tool in understanding systems complexity and for testing and simulating diverse control approaches [8]. The robot structure considered has (6) identical legs and each leg has (3) degree of freedom, in addition to that, all the related points for each joint have been put on the model, the legs numbering as shown in Figure 1, robot's center coordinate o (x_o, y_o, z_o).

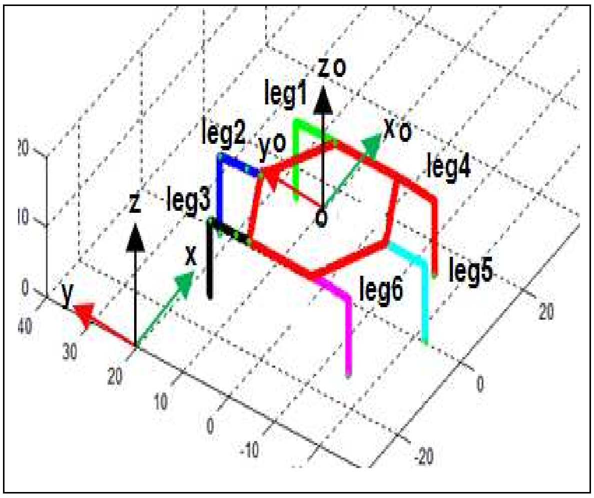


Fig. 1. Hexapod robot structure.

The z-axis pointing up, the x-axis pointing forward and the y-axis pointing left and according to right hand rule. Hexapod robot modeling consisting of two types, one is forward kinematic and its inverse, below will discuss in details for each type of kinematic.

2.1. Forward kinematics for One Leg of hexapod Robot

The successful design of a legged robot depends to a large amount on the leg design chosen. Since all aspects of walking are ultimately governed by the physical limitations of the leg, it is important to select a leg that will allow a maximum range of motion and not inflict unnecessary constraints on the walking. The three-revolute kinematical chain (R_1, R_2, R_3) has been chosen for each leg mechanism in order to imitate the leg structure as shown in Figure 2. A direct geometrical model for each leg mechanism is formulated between the moving frame $o_i(x_i,y_i,z_i)$ of the leg base, where i=1…6, and the fixed frame o (x_o,y_o,z_o) [9].

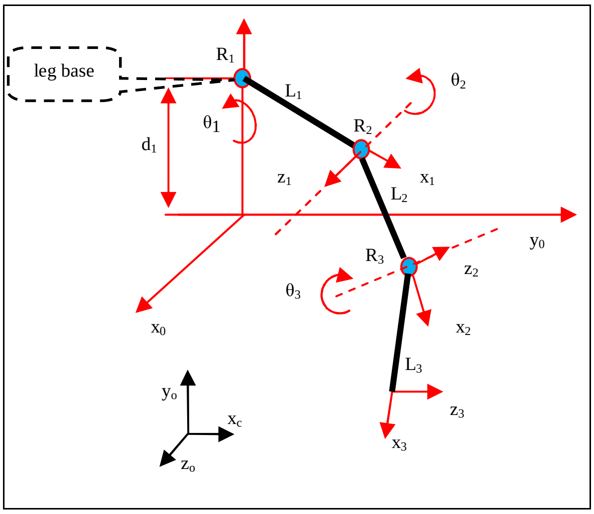


Fig. 2 .Model and coordinates frame for leg kinematics.

In this paper, the BH3-R hexapod robot model is taken as a case study of hexapod robot. The lengths of the hexapod's leg are: L_1 = (2.9 cm), L_2 = (5.7 cm), L_3 = (10.8 cm) [10]. The robot leg frame starts with link (0) which is the point on the robot body where the leg is jointed to; link (1) is the coxa, link (2) is the femur and link (3) is the tibia. Legs are distributed symmetrically around the axis in the direction of motion (x in this case). The general form for the transformation matrix from link (i) to link (i_{-1}) using Denavit Hartenberg parameters is given in the Eq. 1 [9,11]:

$$T_i^{i-1} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\ \cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \ldots(1)$$

The transformation matrix is a series of transformations:

1. Translate d_i along z_{i-1} axis.
2. Rotate $\theta_i$about zi-1 axis.
3. Translate a_i about xi-1 axis (a_i= Li for i=1...3).
4. Rotate α_i about xi-1 axis.

The overall transformation is obtained as a product between three transformation matrixes:

$$T_{coxa}^{base} = T_{coxa}^{femur}\,T_{femur}^{tibia} \quad \ldots(2)$$

Considering Figure 2 and using Eq. 2 the coordinates of the leg tip are:

$$x = \cos\theta_1 * (L_1 + L_2 * \cos\theta_2 + L_3 * \cos(\theta_2 - \theta_3)),$$
$$y = \sin\theta_1 * (L_1 + L_2 * \cos\theta_2 + L_3 * \cos(\theta_2 - \theta_3)),$$
$$z = d_1 + L_2 * \sin\theta_2 + L_3 * \sin(\theta_2 - \theta_3) \quad \ldots(3)$$

Where: d_1 is the distance from the ground to the coxa joint. L_i are the lengths of the leg links.

2.2. Inverse Kinematics using Geometric Approach

The inverse kinematics problem consists of formative the joint angles from a given position and orientation of the end frame. The solution of this problem is significant in order to transform the motion assigned to the end frame into the joint angle motions matching to the desired end frame motion. The goal is to find the three joint variables θ_1, θ_2, and θ_3 corresponding to the desired end frame position. The end frames orientation is not a matter, where only paying attention in its position [9].

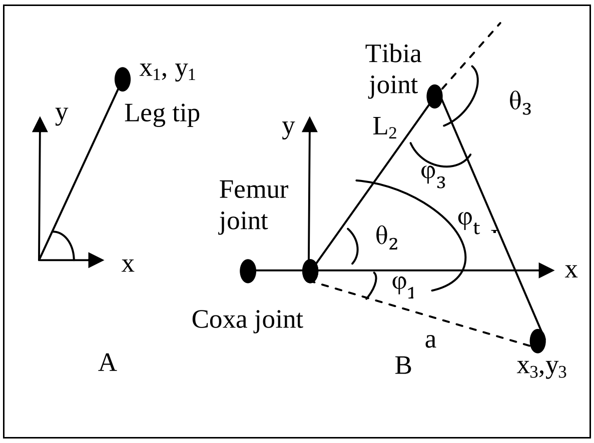


Fig. 3 . Illustrations for solving inverse kinematics.

Using Eq. 3 and considering the following constraints: all joints allow rotation only about one axis, femur and tibia always rotate on parallel axes, and the physical limitation of each joint can determine the joint angle. The coxa joint angle can be found using the following function as can be seen from Figure 3 A.

$$\theta_1 = \tan^{-1}\left(\frac{y_1}{x_1}\right) \quad \ldots(4)$$

In order to determine the other two angles a geometrical approach is considered. The leg tip coordinates were transformed to coxa frame using the transformation matrix below:

$$T_{coxa}^{femur} = \begin{pmatrix} (R_{femur}^{coxa}) & -(R_{femur}^{coxa})^T * d_{femur}^{coxa} \\ 0 & 1 \end{pmatrix} \quad \ldots(5)$$

The angle θ_2 of the femur servo position can be derived directly from the triangle Figure 3 B.

$$\theta_2 = \varphi_t - \varphi_1 \quad \ldots(6)$$

The angle φ_1 is the angle between the x-axis and line a and can be calculated with the following function:

$$\varphi_1 = \tan^{-1}\left(\frac{y_3}{x_3}\right) \quad \ldots(7)$$

Where x_3 and y_3 are the leg tip coordinates in coxa frame. The law of cosine results is applied:

$$\varphi_t = \cos^{-1}\left(\frac{L_2^2 + a^2 - L_3^2}{2 * L_2 * a}\right) \quad \ldots(8)$$

Where:

$$a = \sqrt{x_3^2 + y_3^2} \quad \ldots(9)$$

From the Eq. 6, the femur angle can be found from[9]:

$$\theta_2 = \cos^{-1}\left(\frac{L_2^2 + a^2 - L_3^2}{2 * L_2 * a}\right) - \tan^{-1}(y_3, x_3) \qquad ...(10)$$

By applying the law of cosines, the φ_3 angle is found:

$$\varphi_3 = \cos^{-1}\left(\frac{L_2^2 + L_3^2 - a^2}{2\, L_2 * L_3}\right) \qquad ...(11)$$

Considering Figure 3 B, the θ_3 can be found as follows [9]:

$$\theta_3 = \pi - \varphi_3 \qquad ...(12)$$

3. Workspace of Hexapod's Leg

In this paper the hexapod's leg workspace has been computed and analyzed. Hexapod's leg workspace can defined as the set of reachable points by the end-effector for each foot. These points (positions) depended on the leg orientation (the mechanical limits of the joints). The mechanical limits of the joints restrict leg motion and are a major factor to consider when developing walking algorithm for a hexapod module. The working volumes for each leg are identical because each leg of hexapod has the same geometrical configuration and joint limits; the analyzed of the two approaches to evaluate the constraint workspace for BH3-R hexapod robot [10]. The limits of the joint variables for a representative one leg are shown in Table 1 [10].

Table 1.
The range of angles for one hexapod's leg [10].

Link Name	The range of one robot's leg angle in degree
Coxa	$-90 < \theta_1 < 90$
Femur	$-45 < \theta_2 < 90$
Tibia	$0 < \theta_3 < 135$

These joint variable limits, then, separate the reachable area from the unreachable area. Reachable areas move with the body. The region included within the reachable area is known as the unconstrained working volume (UWV). The constrained working volume (CWV) is defined as a subset of the original working volume, for each leg, that ensures static stability. Therefore, the (CWV) sets soft limits for each leg so as to exclude points from the working volume that may lead to instability. In our case, the working volume is also constrained to prevent leg collisions. An excluded area for hexapod's legs, then, is that part of the reachable area where, if a foot were placed there, instability or leg collision might result.

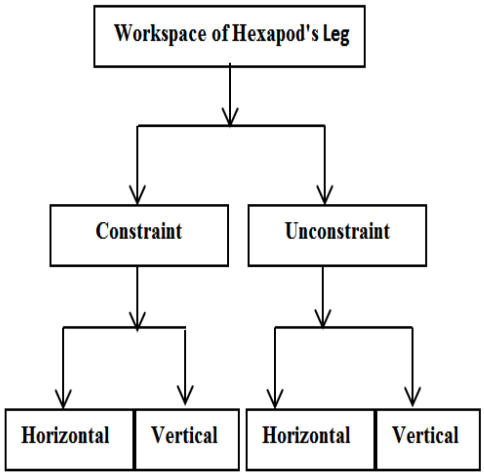


Fig. 4. Flowchart Workspace of hexapod's leg.

Figure 4 shows that the flowchart of workspace. The workspace of robot leg is computed from kinematics and geometry as follow:

3.1. Unconstrained Workspace

The unconstrained horizontal workspace of hexapod leg is the reachable areas include the sections in the xy plane around the individual coxas and within the mechanical joint limits, the y plane equal (30 cm). The unconstrained vertical workspace, or z-plane reachable area, depends on the height of the hexapod's center-of-body above the terrain is (5.5 cm).

To define the maximum unconstrained vertical workspace, if a leg were extended to its fullest, the added lengths of radius body (13.75 cm), coxa (2.9 cm), femur (5.7 cm), and tibia (10.8 cm) y-plane would equal (30 cm). The minimum unconstrained vertical workspace, If a leg were lack extent to its fullest, (i.e $\theta_3 = 135^0$), the y-plane would equal (14.7 cm) while the z-plane equals to (9 cm).

3.2. Constrained Workspace

The calculations of CWV results are used for six basic constraints:

- the height (z = plane) from the ground to the CB (center body of robot) = (10.8 cm) is fixed for minimum, maximum reach, the vertical maximum reach equal (24.25 cm) if θ_3 = 80^0 and minimum reach equal (21 cm) if θ_3 = 97^o,

- the suitable posture of robot = (22.35 cm) if θ_3 = 90^o,
- The terrain is flat,
- The legs are not allowed to collide or overlap, and
- The horizontal workspace of hexapod leg is the reachable areas include the sections in the xy plane around the individual coxas, y-plane = 24.25 cm and within the mechanical joint limits but in this case limit joint (half range of coxa angle is taken in order not to the legs collide) so the range is $(-45 < \theta_1 < 45)$ degree.

Another approach for constrained workspace is derived, the more details in [12], [13]. For the hexagonal model the mathematically Eq. 13 for the radius of the annulus is :

$$r_{max}^2 = (r_{min} + Q)^2 + \left(\frac{1}{2} * P\right)^2 \qquad \dots (13)$$

Where: r_{max} , r_{min}, Q, P defined by Figure 5.

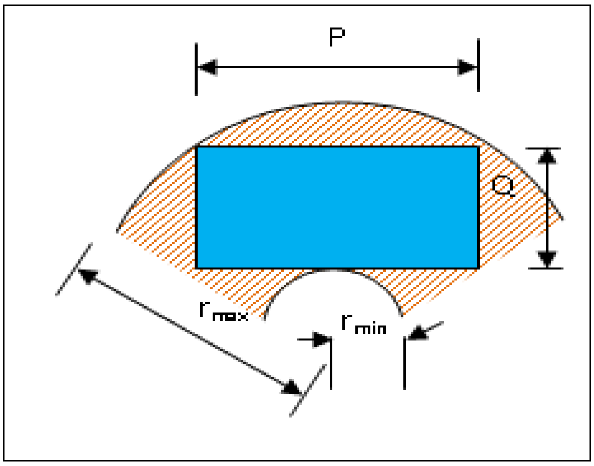


Fig. 5. The relationship between the reachable area and annuls.

And the rectangular area is the reachable area of each leg of robot, for our hexapod robot r_{max} = (10.5 cm) from coxa joint. Added the length of center robot (13.75 cm), r_{max} = (24.25 cm). The center of leg tip point is (22.35 cm) that it is equal to the posture robot in method1 above comparing between two constraints workspaces methods are found that the maximum reaches of the leg are equal for our hexapod robot.

4. Modified Classical Stability Margins Analysis Approach of Hexapod Robot

The first gait of the hexapod robot is the tripod gait. In this gait the three legs stay on the ground (support pattern) while the other legs are on the air. The analysis of static stability depended on the Eq. 14 (the triple equation in the Figure 6) [14] that only computes the S_1 where S_2 and S_3 are evaluated from the same pervious equation but with changing the coordinates of legs for each S_1, S_2 as in the Figure 6 of three triangles and there are two conditions to set the robot stable first if S_1, S_2 and S_3 are >= zero, the tripod is considered stable other, the tripod is considered unstable more details in [14].

From the definition of "stability margin," (sm), is the shortest distance from the vertical projection of the center of robot to the boundaries of the support pattern in the horizontal plane [15] the proposed method is explained below:

In Figure 6 L_1 is derived in the Eq. 16 (the distance line between two points) and the same thing of L_2 is computed, L_3 for other legs, each L is considered as a base of the one triangle while the areas of the S_1, S_2 and S_3 are previously computed so that the stability margin is the shortest perpendicular distances from L_1, L_2 and L_3 to the center of robot (H_1, H_2, H_3 respectively). H_1 is computed as Eq. 17 as well as the H_2, H_3 are computed in the same manner.

the stability margins are computed and analyzed for all cases of the hexapod legs motion for three gaits (tripod, ripple and wave) for example the support pattern of tripod when robot lifts legs (1, 3 and 5) :

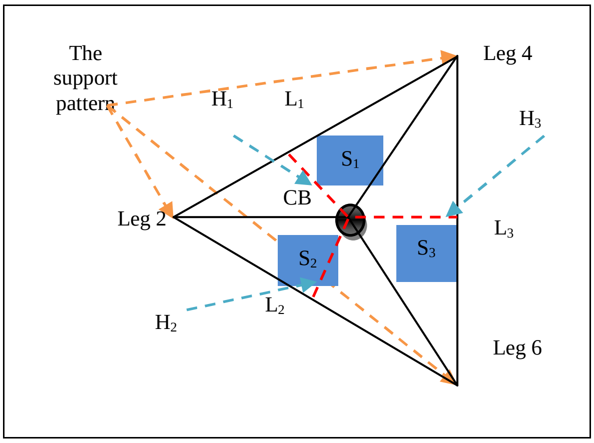


Fig. 6. The stability analysis for the tripod gait when legs (2, 6 and 4) on the ground and legs (1, 3 and 5) on the air.

The triple equation of the Figure 6 is:

$$S_1 = \frac{1}{2}\begin{vmatrix} 1 & 1 & 1 \\ x_{CB} & x_4 & x_2 \\ y_{CB} & y_4 & y_2 \end{vmatrix} \qquad \dots (14)$$

Where (x_{CB}, y_{CB}) the coordinate of center body, (x_2, y_2) the coordinate of Leg 2, (x_4, y_4) the coordinate of Leg 4.

The simplification of the Eq. 14 :

$$S_1 = \frac{1}{2}\left[(x_4 - x_{CB})(y_2 - y_{CB}) - (x_2 - x_{CB})\left((y_4 - y_{CB})\right)\right] \quad ...(15)$$

$$L_1 = \text{sqrt}\left((x_2 - x_4)^2 + (y_2 - y_4)^2\right) \quad ...(16)$$

Where L_1 is the distance between two points

$$H_1 = 2 * \left(\frac{S_1}{L_1}\right) \quad ...(17)$$

From Figure 6 the stability margin are computed as:

$$sm_1 = \min(H_1, H_2, H_3) \quad ...(18)$$

sm_1 is the stability margin of the support pattern of legs (2, 4 and 6) similarly, the sm_2 is derived for other three legs when (1, 3 and 5). Besides that, Eq. 18 is derived for the other gaits of robot (wave and ripple).

5. Walking, Mechanism of Leg Motion and Path Planning of Hexapod Robot

The mechanism of leg motion is very complex problem that each leg is forward and back motion. It derived from insect motion that has two phases: swing (the leg in the air) and stance (the leg in the ground) phases [3]. The equations of motion in [16] are derived for two phases. The walking of hexapod robot is developed by combing the stance phase [16] explained by Eq. 19 and the swing phase [17] as in Eq. 20 to get our modified smooth gait for one hexapod's leg as below:

$$x_{i+1} = x_i - v * T * \cos(\phi),$$
$$y_{i+1} = y_i - v * T * \sin(\phi) \quad ...(19)$$

Where x_i, y_i the coordinates of leg tip derived from the forward kinematic, ϕ is the direction of motion, T is the period required to complete one cycle and changes during type gait and v describes how many centimeters per gait cycle the hexapod robot should move.

The equations in swing phase are:

$$x_{i+1} = 2 * \dot{x}_l * dt_{step}\left(1 - \cos\left(\frac{\pi t}{dt_{step}}\right)\right),$$
$$y_{i+1} = 2 * \dot{y}_l * dt_{step}\left(1 - \cos\left(\frac{\pi t}{dt_{step}}\right)\right),$$
$$z_{i+1} = h * \left(1 - \cos\left(\frac{\pi t}{dt_{step}}\right)\right) \quad ...(20)$$

$\dot{x}_l, \dot{y}_l$ are the speed of the hexapod robot's truck in x and y directions, dt_{step} is the time duration for each step and h is the height of each step. The movement of the center of body that moves from start point to the goal point so the new center point [14] is calculated as:

$$x_{c_{i+1}} = x_{c_i} + l * \cos(\phi),$$
$$y_{c_{i+1}} = y_{ci} + l * \sin(\phi) \quad ...(21)$$

Where l is the step size.

The path planning start from point (0,0) cm and end with goal point (500,0)cm for the straight line.

6. Stability Margins Enhancement using Genetic Algorithm

The results of sequences of three main gaits for hexapod robot are found the range values for the stability margins as mentioned above. Each gait of hexapod robot, has the sequence of gait such as the tripod gait has two sequences, the first sequence lifts legs (1, 3 and 5) where the legs (2, 4 and 6) on the ground. The second sequence lifts legs (2, 4 and 6) where the legs (1, 3 and 5) are on the ground.

In the proposed method, an intelligent method which is (GA) has been applied to find the best stability margin during each sequence in each gait. While modified classical stability margins analysis method which used to find the range values for stability margins is considered as constraints for Genetic Algorithm to find the best stability margins based on these constraints. Also, the genetic algorithm has been applied to find the best positions of legs tips as described below:

A. Parameters Initialization of Genetic Algorithm

The initial populations for genetic algorithm are the coordinates of each leg's tip (x_i, y_i) and the coordinates of center body (x_{CBi}, y_{CBi}) while the (z_i) is constant (the motion of hexapod robot on the flat plane). Chromosomes (individuals) represent the solutions for optimization problem. In the proposed work, the better results of new stable population are evaluated. These results are considered as initial coordinate (x_i, y_i) for walking of the hexapod robot. These stable positions are repeated till hexapod robot reaches to the goal point.

The size of genes in each chromosome is various according to the type of gait (support pattern for each sequence) for example the size of

chromosomes equals to eight variables in tripod gait. The first sequence in tripod gait when lifting legs (1, 3 and 5) where legs (2, 4 and 6) on the ground have been calculated with center body coordinates as the following formula:
$\mathrm{chromosome} = [x_c\ y_c\ x_2\ y_2\ x_6\ y_6\ x_4\ y_4]$.
The other sequences of hexapod gaits types are formulated as in the above example and according to each gait.

B. Fitness Function:

The fitness function of GA is used as minimization of the cost function (stability margins) as derived previously, Where each $\mathrm{sm} = \min(H_1, H_2, \ldots, H_6)$ and the H_i defined in section (4). For example ,the fitness function of tripod gait equals to stability margin (sm) is selected according to the each sequence of each gait such as the Eq. 18

The idea of proposed approach is different from the approach in [17]. The difference is that the researchers in [17] that the minimum fitness stability margin is squared value (fitness function $=sm^2$) in order to get the high values of stability margin (sm), while in proposed work, the minimum fitness stability margin is (fitness function =sm) and all values are high and within the constraints of legs tips without need to square the stability margin (sm). All cases of our approach results of the stability margin are within the ranges of stability margins from modified classical analysis method.

In the GA, the best stability margins are evaluated while in the modified classical approach the ranges of the stability margins are obtained. The all cases of the fitness equations for three gaits are derived from the modified classical stability method where in each sequence there is fitness function as an example for Eq. 18 is the fitness function of tripod gait for the first sequence (where the robot lifting legs (1, 3 and 5) and legs (2, 4 and 6) are on the ground).

C. Crossover Operation

The main processing of crossover is to get two parents of coordinates of leg's tips and the center body coordinates and producing from them the children. Crossover operator is applied to produce a better offspring (children).

D. Mutation Operation

After the crossover operation, the output string from crossover is subjected to mutation process.

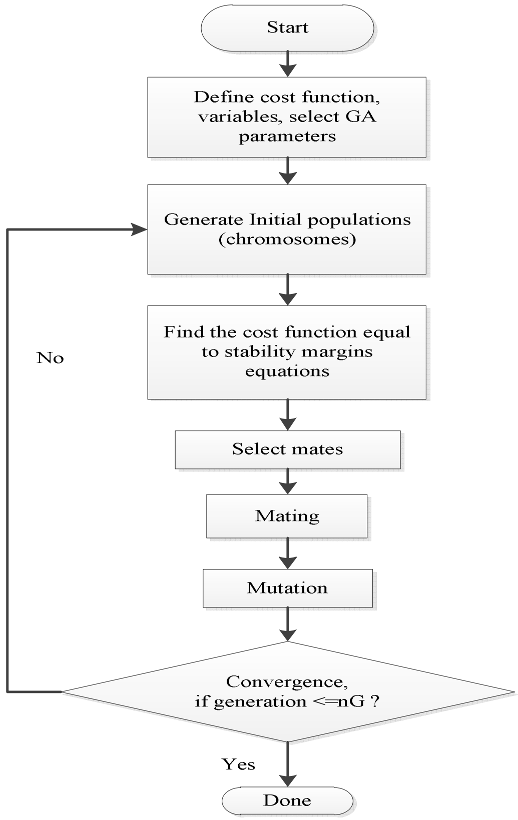


Fig. 7. Proposed flowchart of GA.

7. Flowchart of Proposed Genetic Algorithm

After complete the modified classical method, below will describe the developed method using Genetic Algorithm. In the Figure 7 shows that flowchart of proposed Genetic Algorithm. It has consists of steps where described as below:

- Defined the variables which determined the leg's tip of hexapod robot (chromosomes).
- Generate the coordinates of leg's tip and center point of body (chromosomes).
- Find the cost function (stability margins equations as in section (4) to get the best stability margin for each sequence for each gait.
- Select mates, mating, and mutation.
- Convergences condition, if the generation <= nG (100 generations).
- Done.

8. Simulation Results

The simulation results consist of two approaches where illustrated as below:

8.1. The Modified Classical Stability Margins

Analysis of the stability margins above for three gaits (ripple, wave and tripod) are simulated for each gait within the steps as below:

a- The wave gait cases

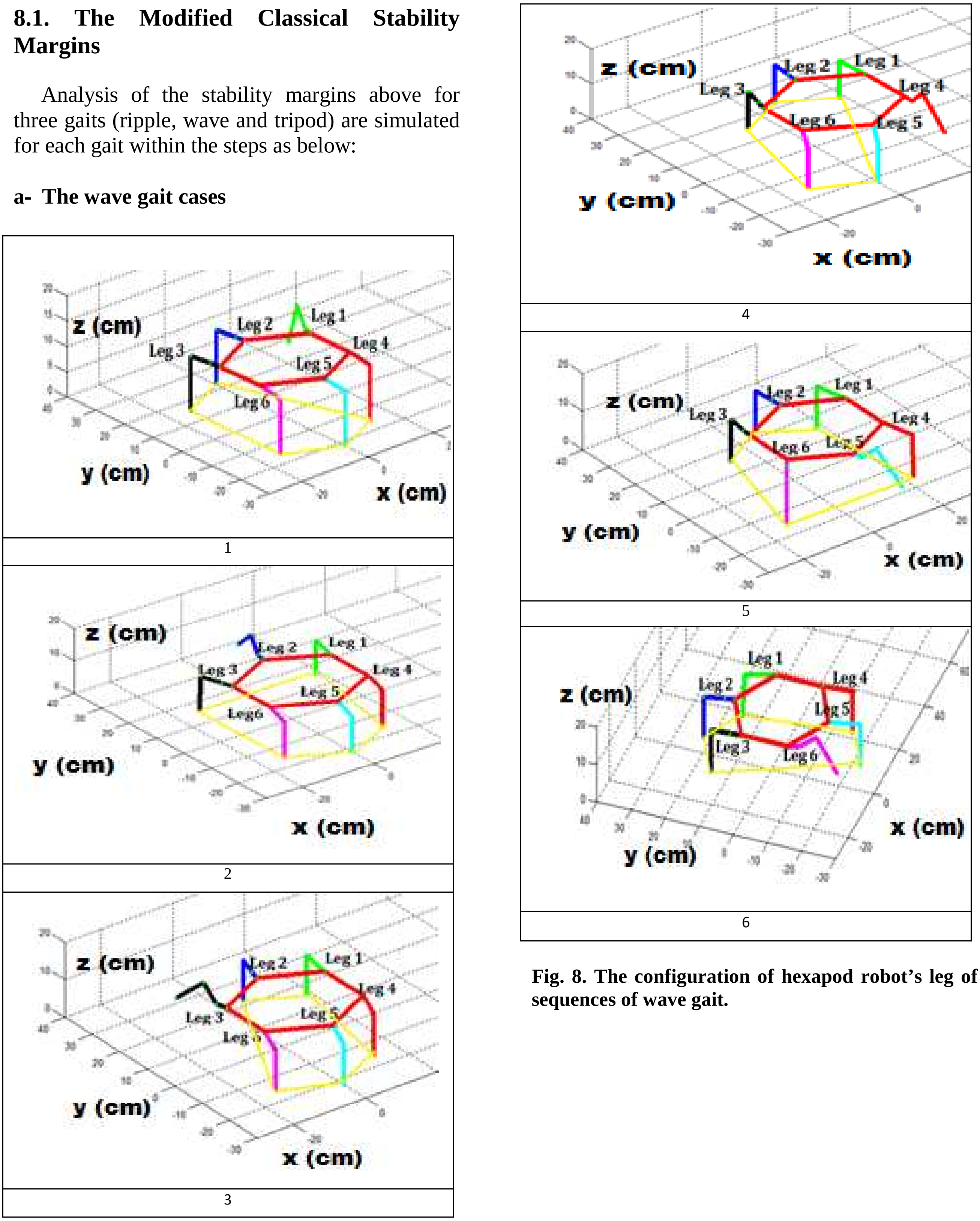


Fig. 8. The configuration of hexapod robot's leg of sequences of wave gait.

b- The ripple gait cases

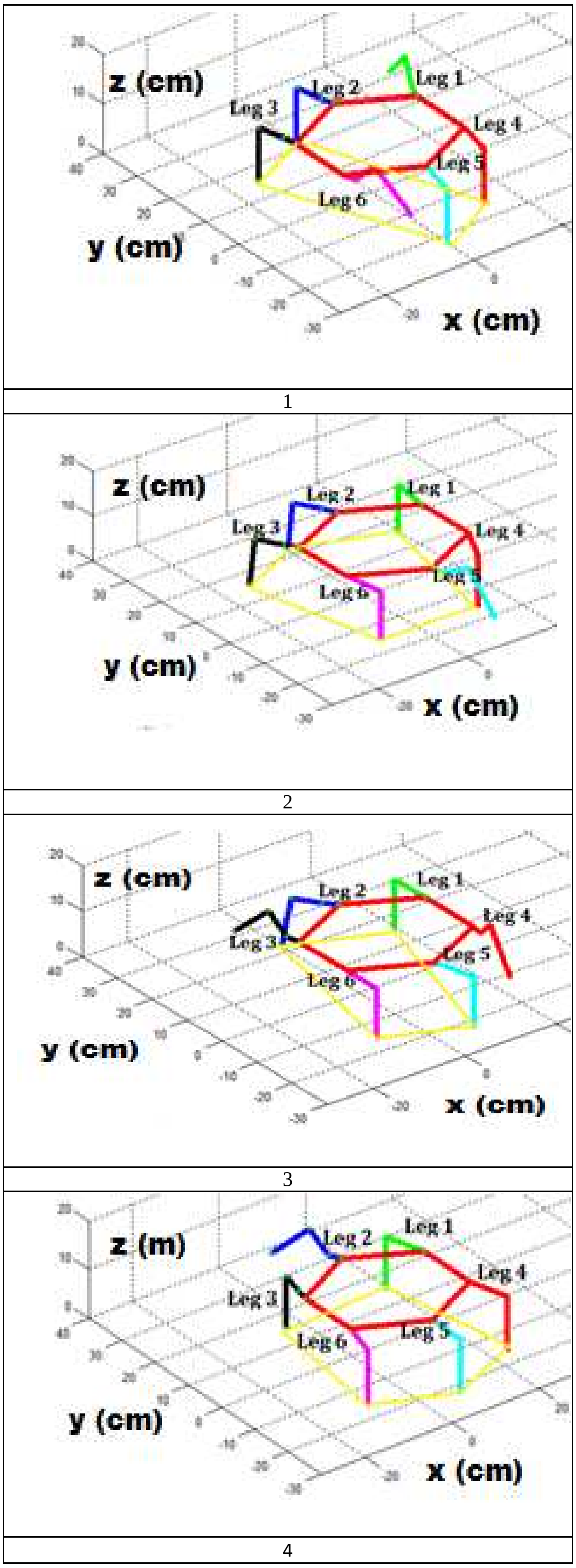


Fig. 9. The configuration of hexapod robot's leg of sequences of ripple gait.

c- The tripod gait cases

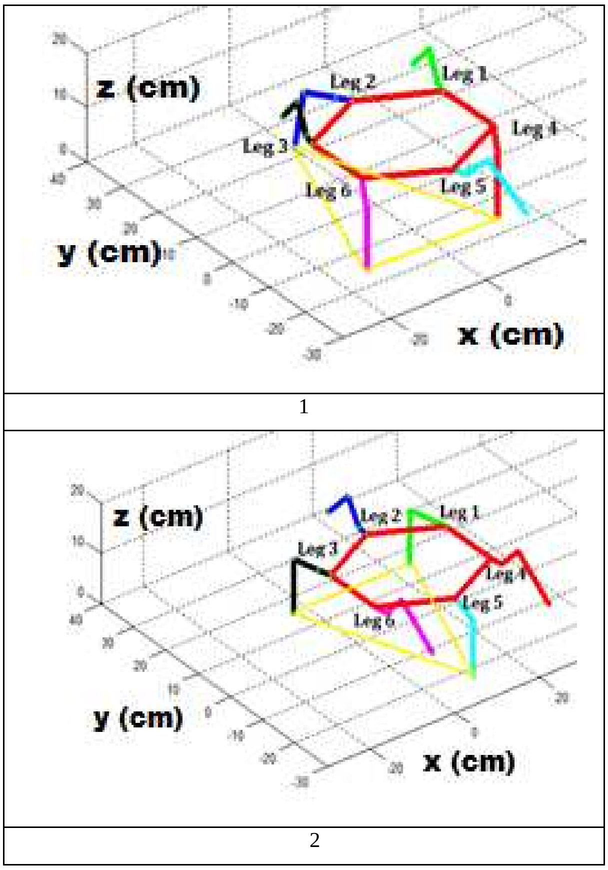
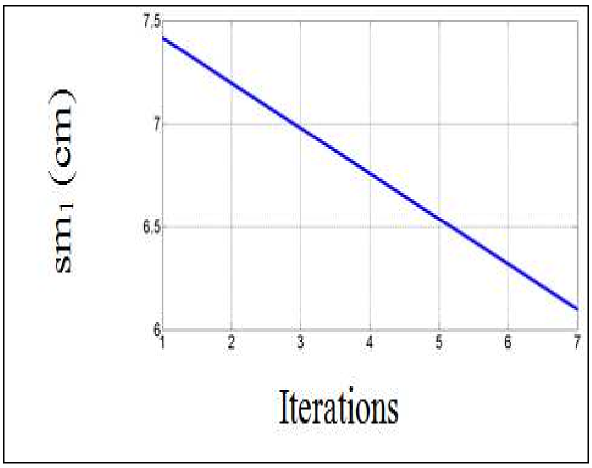
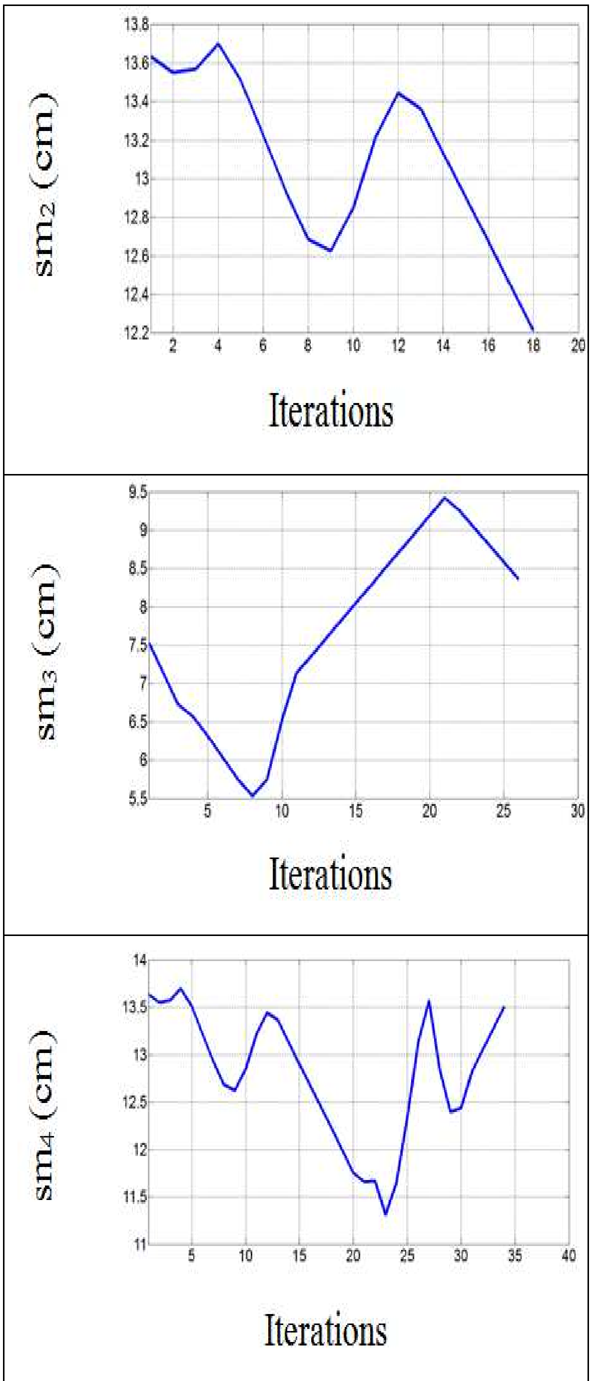


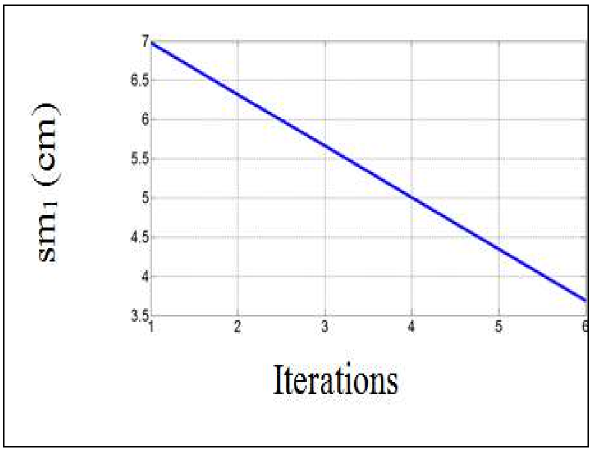
Fig. 10. The configuration of hexapod robot's leg of sequences of tripod gait.

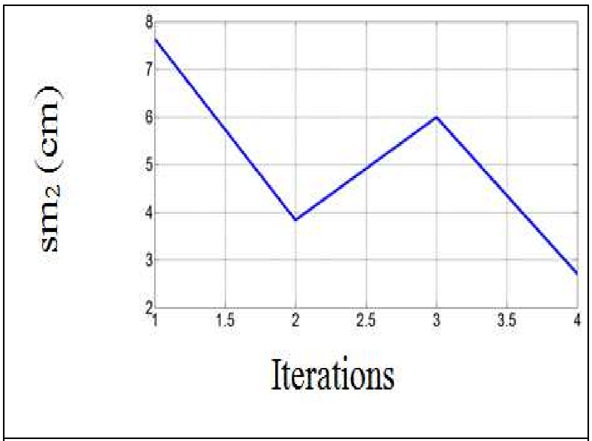
The figures (8-10) show that the configurations of hexapod robot's legs for three gaits. The yellow lines indicated to the support patterns. From support patterns the (sm) is evaluated for each sequence in every gait and the simulation results of all stability margins are described in simulations below:



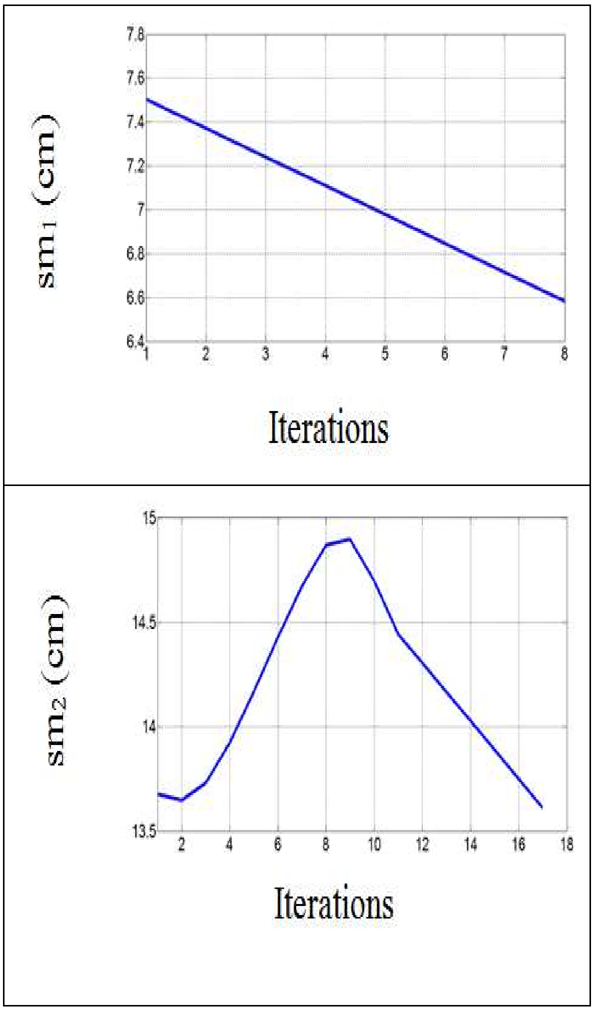

sm_2 (cm)
Iterations
sm_3 (cm)
Iterations
sm_4 (cm)
Iterations

(a)


sm_1 (cm)
Iterations


sm_2 (cm)
Iterations

(b)


sm_1 (cm)
Iterations
sm_2 (cm)
Iterations

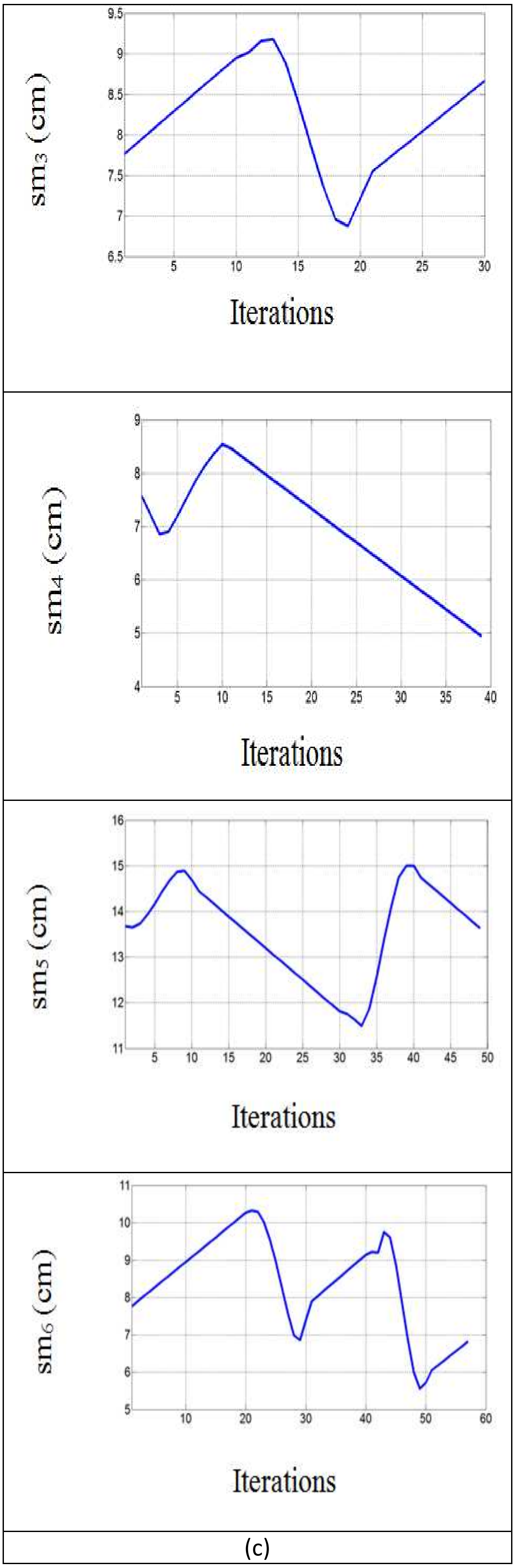


Fig. 11. Minimum and maximum stability margins for, (a) ripple gait, (b) tripod gait, and (c) wave gait.

In Figure 11 shows that the stable range of stability margins for three gaits and these values are considered the constraints to the genetic algorithm of our proposed work.

8.2. Best Stability Margins using Genetic Algorithm

From the study in the section (4), the results of best stability margins are shown in below:

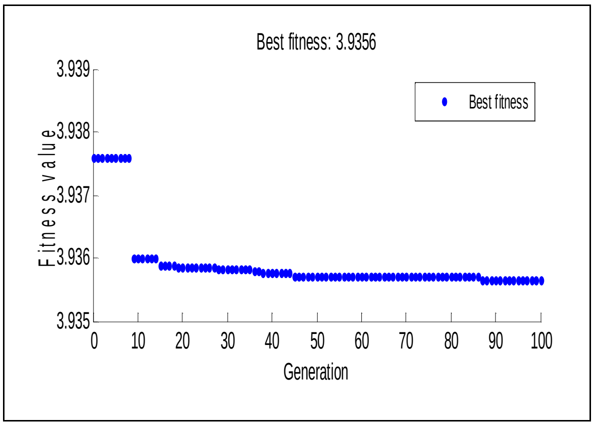


Fig. 12. The best fitness value for tripod gait when the legs (2, 6, and 4) are on the ground and lifting legs (1, 3 and 5).

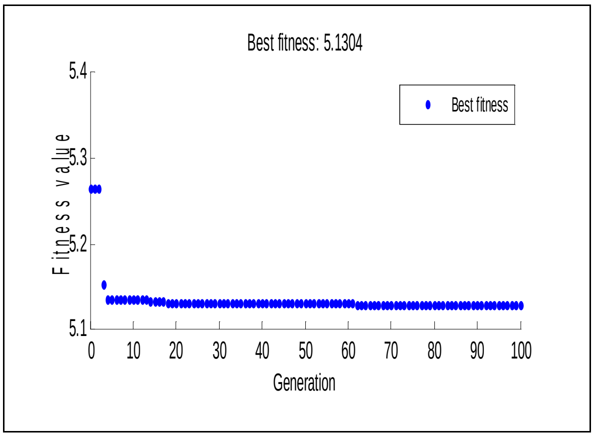


Fig. 13. The best fitness value for tripod gait when the legs (1, 3 and 5) are on the ground and lifting legs (2, 6 and 4).

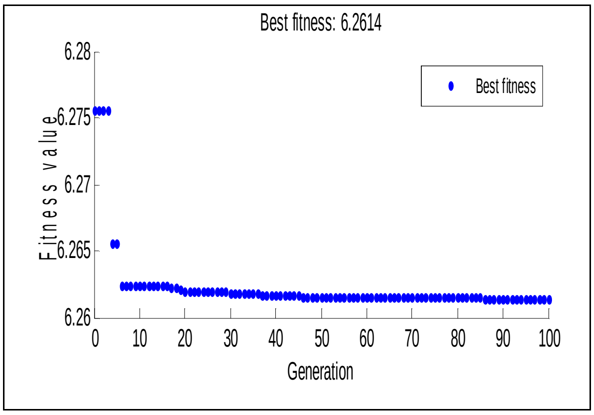


Fig. 14. The best fitness value for ripple gait when the legs (2, 3, 5, and 4) are on the ground and lifting legs (1, and 6).

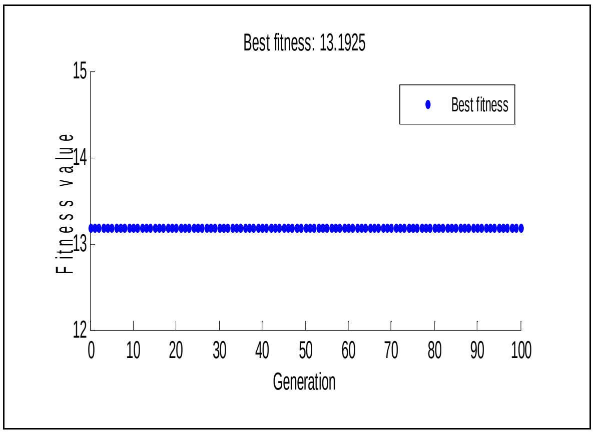


Fig. 15. The best fitness value for ripple gait when the legs (4, 1, 2, 3 and 6) on the ground and lifting leg (5).

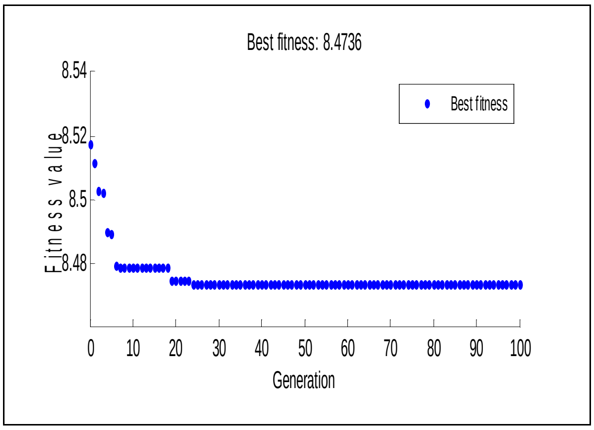


Fig. 16. Best fitness value for ripple gait when the legs (1,2,3,6 and 5) on the ground and lifting leg (3 and 4).

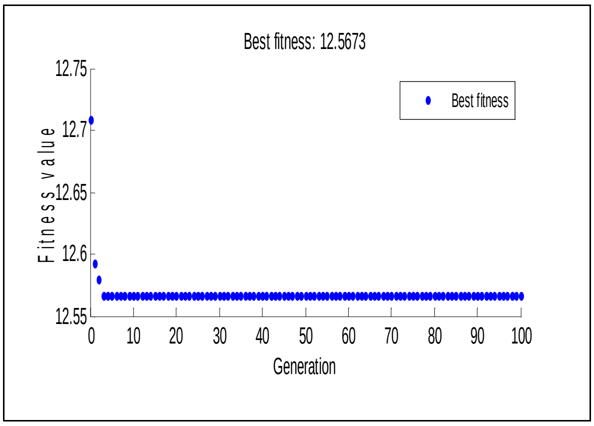


Fig. 17. The best fitness value for ripple gait when the legs (1, 3, 6, 5 and 4) on the ground and lifting leg (2).

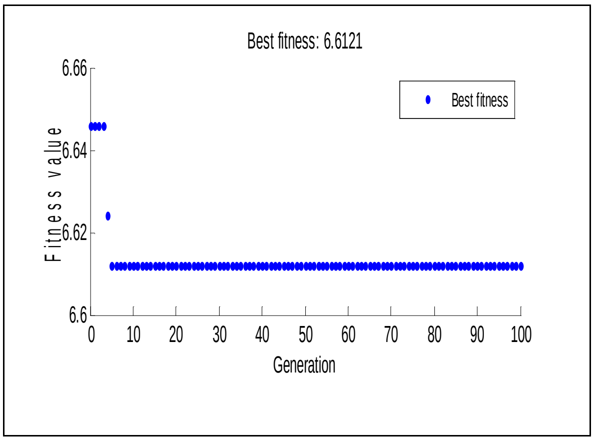


Fig. 18. The best fitness value for wave gait when the legs (2, 3, 6, 5 and 4) on the ground and lifting leg (1).

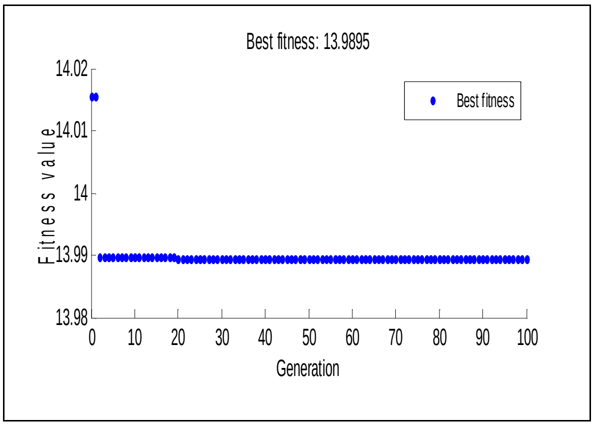


Fig. 19. The best fitness value for wave gait when the legs (1, 3, 6, 5 and 4) on the ground and lifting (2).

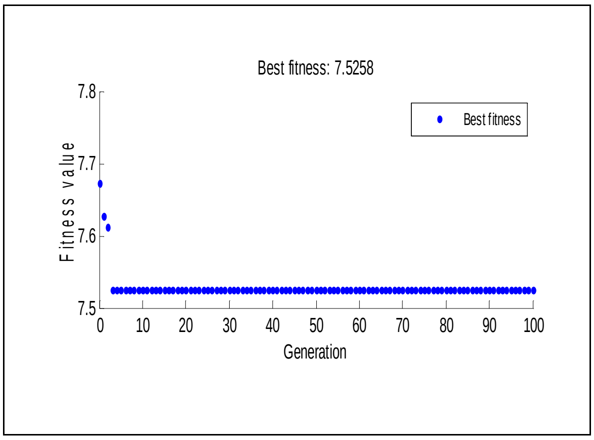


Fig. 20. The best fitness value for wave gait when the legs (1, 2, 6, 5 and 4) on the ground and lifting leg (3).

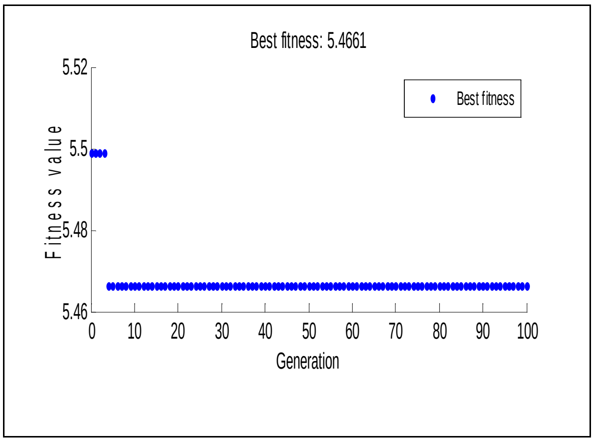


Fig. 21. The best fitness value for wave gait when the legs (1, 2, 3, 6 and 5) on the ground and lifting leg (4).

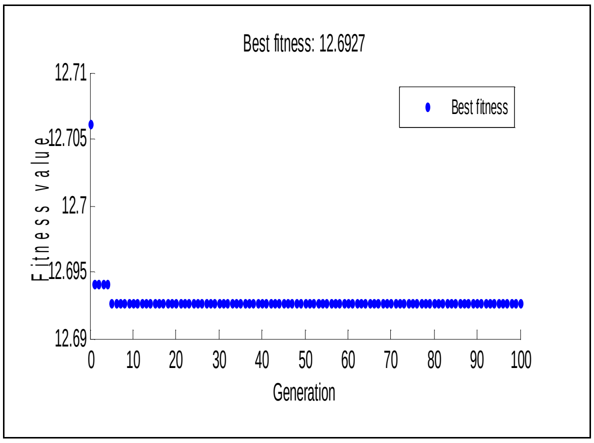


Fig. 22. The best fitness value for wave gait when the legs (1, 2, 3, 6 and 4) on the ground and lifting leg (5).

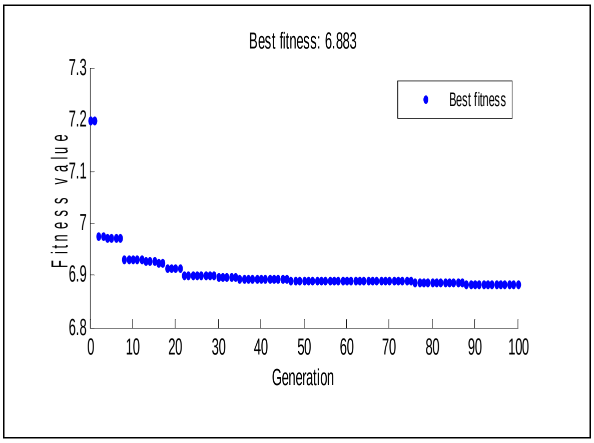


Fig. 23. The best fitness value for wave gait when the legs (1, 2, 3, 5 and 4) on the ground and lifting leg (6).

The above Figures (12 - 23) show that the best stability margins for each sequence in each gait and all the stability margins are within the range of constraints that described in classical stability margins analyses method.

The analysis equations of Eq. 21 used of find the next points of the hexapod center body and the errors center body of the path planning for two approaches is shown in Table 2, below:

Table 2,
Shows that the errors of two approaches modified classical stability margins and stability margins Enhanement using GA.

Errors path planning of modified classical stability margins	**Errors path planning of stability margins Enhancement using GA**
1- Tripod gait has less error value equals (8.3630e-004) cm. 2- Wave gait has less error value equals (0.0023) cm. 3- Ripple gait has great error value equals (0.0520) cm.	1- Tripod gait has less error value equals (2.3590e-004) cm. 2- Wave gait has error value equals (0.0012) cm. 3- Ripple gait has great error value equals (0.0196) cm.

The genetic algorithm here works as off-line and getting the new stable coordinates of legs tips of hexapod robot (new populations) before robot start walking .From these coordinates are selected, the best points of the center body in (x , y) plane are calculated according to the best stability margins values.

9. Conclusion

In this paper the stability margins are analyzed for all gaits of hexapod robot in two approaches first is the modified classical approach and second, is the stability margins enhancement using genetic algorithm.

In first approach, the range of stability margins values are evaluated for each sequence in every gait where the hexapod walking from start point (0,0) cm to the goal point (500,0) cm. For the second approach, the best stability margins for each sequence in every gait are calculated and the results is useful to get best stable path planning with smaller error than the first approach for three gaits of hexapod robot as in Table 2, above .Also in the second approach and according to the best stability margins values.

The better new stable coordinates (positions of legs) are gotten than stable coordinates of first approach. In addition, the better new stable center body coordinates are evaluated than center body coordinates in the first approach

Notation

d_i	translation along z_{i-1} axis
$a_i = L_i$	link length about x_{i-1} axis
T_i^{i-1}	forward kinematic matrix
x, y, z	coordinates of hexapod's leg
r_{max}	maximum length of leg's workspace
r_{min}	minimum length of leg's workspace
Q, P	lengths of rectangular reachable area
S_1	triple equation
H_1	vertical line from the center point of the robot's body to the middle of the base (L_1)
sm	stability margin
x_{i+1}, y_{i+1}	backward smooth motion
x_{i+1}, y_{i+1}, z_{i+1}	forward smooth motion
ϕ	direction of motion
T	period required to complete one cycle
l	step size
$\dot{x}_1$,$\dot{y}_1$	are the speed of the hexapod robot's truck in x and y directions
dt_{step}	time duration for each step
h	height of each step
$x_{c_{i+1}}$, $y_{c_{i+1}}$	new center coordinates of hexapod's body
x_{CBi}, y_{CBi}	center coordinates of hexapod's body
v	represents speed of how centimeter per gait cycle the robot should move
GA	Genetic Algorithm

Greek Letters

θ_i	rotation angle about z_{i-1} axis
α_i	rotation angle about x_{i-1} axis
φ_1	angle between the x-axis and line a

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تحسين الاستقرارية الثابتة للهكسابود روبوت باستخدام الخوارزمية الجينية

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الخلاصة

هكسابود روبوت هو روبوت ميكانيكي مرن ذو ستة ارجل. له القدرة على المشي على الارض. الهكسابود روبوت يشبه الحشرة لذلك له حركاتها نفسها. هذه الحركات هي ثلاثية القوام ، متموجة و تموج. الهكسابود روبوت يحتاج للبقاء مستقرا بشكل ثابت في كل الاوقات للحركات و لكي لا يقع تبقى ثلاثة أرجل او اكثر على الارض بصورة مستمرة. الاستقرارية الثابتة الامنة للمشي تدعى (stability margin). في هذه الورقة تم اشتقاق علم الحركة الامامي والخلفي لكل ساق في الهكسابود روبوت لغرض رسم موديل الهكسابود روبوت ببرنامج MATLAB R2010a وكذلك رسم حركاته وتم اشتقاق معادلات مساحات العمل الفرعية المحددة لكل ساق. حجوم مساحات العمل الفرعية ممكن تعريفها بانها تحدث عندما الارجل تتحرك بدون اصطدام مع بعضها وكذلك تعمل على حفظ الارجل مستقرة بمنعها من السقوط لكل حركة. تم تحليل وتحسين الحركة الناعمة لكلا الطورين طور التوقف وطور التأرجح.

في العمل المقترح تم التركيز على طريقتين، الاولى الطريقة الكلاسيكية المعدلة لل (stability margins). في هذه الطريقة، تم حساب مجموعة من قيم ال (stability margins) لكل الحركات. الطريقة الثانية سميت ب stability margins باستخدام الخوارزمية الجينية التي حسنت الاستقرارية الثابتة بحصولها على افضل قيم لل stability margins للهكسابود روبوت وهذه النتائج مفيدة في الحصول على افضل مسار خطي للحركة بخطأ اقل من الطريقة الاولى و قد تم الحصول على احداثيات مستقرة جديدة لنهايات الارجل افضل من الطريقة الاولى . بلاضافة الى ذلك، في الطريقة الثانية كانت احداثيات مركز جسم الروبوت افضل من الطريقة الاولى.