Hexapod Robot Static Stability Analysis using Genetic Algorithm Simulation and Experimental Work

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Abstract

BH3-R hexapod robot has six legs for walking with a round body. The mechanical structure of hexapod robot like insect so that it has three main gaits: wave gait, ripple gait, and tripod gait. The main problem of hexapod robot is to get the best static stable during its walking. In the proposed approach, the static stability analysis using Genetic Algorithm (GA) is implemented experimentally for three gaits. The result has been get the stable best coordinates of hexapod legs tips (x_i, y_i, z_i) and the stable best coordinates of the center body coordinates of hexapod legs tips (x_{ci}, y_{ci}) according to the best static stability. In proposed work, stability margin analysis is used as fitness function in Genetic Algorithm (GA) for each gait. The results of stability margins are evaluated and the hexapod robot walking according to new stable coordinates of legs tips. Practically the velocities of the wave gait is lowest gait while, the ripple is more velocity than wave but the tripod gait is fastest gait. The error of real path planning of BH3-R hexapod robot is small in all three gaits. The equations of Pulse Width Modulation (PWM) for three joints angles in each leg are proposed experimentally for BH3-R hexapod robot.

Keywords: Hexapod Robot, Wave Gait, Ripple Gait, Tripod Gait, Static Stability, Fitness Function, Pulse Width Modulation.

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1- Introduction

Hexapod robot is one of the walking robots having six legs where the legs are consist of multiple servo joints. The design of hexapod robot like insect so that it has three main gaits: Wave gait, Ripple gait, and Tripod gait [1]. The fastest gait is called tripod gait, the sequence of tripod gait is three legs stay on the ground, while the other legs in the air, in addition, ripple gait (tetrapod) is the medium speed, the sequence in this gait contains the four legs are stay on the ground while two legs are swing in the air and the third type of gait is called wave gait, its slowest gait because the sequence contains one leg swings in the air while five legs stay on the ground [2, 3]. The gait of hexapod robot is called statically stable gait if the vertical projection of the center of mass of the body on to a horizontal plane is within the support area [4]. An intelligent algorithm using Genetic Algorithm (GA) used for hexapod robot like in [5] a hexapod simulated robot has been walked in an approximate straight line using GA, but the efficiency of the gait was poor and the stability is satisfied.

The static stability analysis for three gaits (tripod, ripple and wave) of hexapod robot has been explained by divided each gait into sequences. For example, in tripod gait the hexapod has two sequences; the first sequence events when lifting three odd legs and the other even legs are down. The second sequence events when lifting three even legs and the other odd legs are down. In each sequence there is one triangle of hexapod robot projection and the stability margin is computed by modified classical stability margin approach as:

$$\mathrm{sm}_1 = \min\,(\mathrm{H}_1\,, \mathrm{H}_2, \mathrm{H}_3) \qquad (1)$$

Where, (H_i) is the vertical line from the center point of the robot's body to the middle of the base for each triangle. The modeling of hexapod robot has been analyzed, where the modeling is included kinematics and its inverse kinematics, besides that, the constraints workspaces for six hexapod robot legs are calculated [6].

In this paper, GA algorithm is implemented on real hexapod robot experimentally. The procedure of this algorithm is explained in details as in proposed flowchart below:

2- Hexapod Robot Static Stability Analysis using Genetic Algorithm Experimentally

The GA algorithm is implemented on BH3-R hexapod robot experimentally. The BH3-R robot's round body symmetry makes this a very unique hexapod walker. The three DOF (degree of freedom) leg design provides the flexibility required to walk in any direction. The robot uses 18 HS-485 servos for the legs [7]. The specifications of BH3-R hexapod robot are in [8].

After evaluation the constraint workspace of each leg [6], the coordinates of hexapod legs tips (x_i, y_i, z_i) and the center body coordinates of hexapod legs tips (x_{ci}, y_{ci}) have been entered as inputs to GA algorithm.

The output of the GA algorithm are the new coordinates of hexapod legs tips (x_i, y_i, z_i) and the center body coordinates of hexapod legs tips (x_{ci}, y_{ci}) (better results of new stable populations have been obtained) and the minimum stability margins for every gait.

- The initial populations of GA are the coordinates of each leg's tip (x_i, y_i) and the coordinates of body center (x_{BCi}, y_{BCi}), 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, better results of new stable populations have been obtained. These results are considered as initial coordinate (x_i, y_i) for walking of the hexapod robot. The size of chromosomes is taken according to the sequences of each gait as described in introduction for example. The first sequence in tripod gait when lifting legs (1,3, and 5) where legs (2,4, and 6) on the ground has been calculated with body center coordinates as the formula below: $\text{chromosome} = [x_c\ y_c\ x_2\ y_2\ x_6\ y_6\ x_4\ y_4]$
- Fitness Function: The objective function of GA is selected for our proposed method as minimization of the cost function (stability margins), as in Equation(1)
  In this proposed approach of GA, the best stability margin has been obtained, while range stability margins values have been obtained in the modified classical stability margin approach. The stability margin (sm) was selected according to the each sequence of each gait. The minimum fitness stability margin is squared value (fitness function=sm^2) in order to get the high values of stability margin (sm) [9], while in our proposed work, the minimum fitness stability margin is (fitness function=sm) and all values are high without need to square the stability margin (sm).

- Crossover operation: Crossover operator is applied to produce a better offsprings (children) and The crossover probability is 0.8
- Mutation Operation: The output string from crossover is subjected to mutation process. The adaptive feasible mutation method is used. In this method the populations are generated randomly.
- Then chosen the one smooth gait from three gaits in order to move the BH3-R hexapod robot, the new stable coordinates of legs tips are generated from GA approach.
- The final new stable coordinates of legs tips for BH3-R hexapod robot are converted to the joint angles using inverse kinematics.
- Control on hexapod motors: practically, these angles are converted to the Pulse Width Modulation (PWM) (τ_j) where, j=1…3 for every link. The motor command has a bipolar-range (+/-) to drive the robot link with positive or negative changing steps. The change in the joint angle is converted into the motor command signal (τ_j) which is sent to the joint motor of the corresponding hexapod robot link to move it. These outputs (τ_j) for every link is derived from three angles ($\theta_1, \theta_2, \theta_3$) in one leg and there are three different angles based on joint direction as in the following Equations:

$$\tau_1 = 9.25\,\theta_1 + 1500 \quad (2)$$

$$\tau_2 = -2.833\,\theta_2 + 1500 \quad (3)$$

$$\tau_3 = -6.666\,\theta_3 + 1500 \quad (4)$$

Where, τ_1 belongs to the coxa joint in two directions (CW and CCW) respectively. τ_2 Belongs to the femur joint in two directions (up and down) respectively. τ_3 belongs to the tibia joint in posture case.

3- Implementation of Hexapod Path Planning System

The aim of the experimental part of this work is to get the stable path planning for hexapod robot based on three types of gaits (tripod, ripple and wave). In this regard during the experiment, the proposed method is to find stable path planning using GA and getting better coordinates and best stability margins compared with the classical method described in chapter three for each sequence in each gait. These coordinates have been converted into angles using inverse kinematic, where these angles are converted into Pulse Width Modulation (PWM) and transmitted to each servo motor which attached to the link of leg.

The main concept of the experimental work is depends on computing and converting the stable angles of leg's tips into the PWMs, then the PWMs are feed using Maestro application to drive the servo motors of hexapod. The Mini-Maestro controller consists of a compiler which is used to write sequences of three gaits. The Mini-Maestro connected to PC via serial port to transfer the data (sequences) from Maestro application to the electronic card. The microcontroller has a memory which is used to contain the program compiled by Maestro program. In addition, the Mini-Maestro consists of servo motor driver which is used to drive the motor by computing and then feeding the PWM to each servo, as shown in Figure (1).

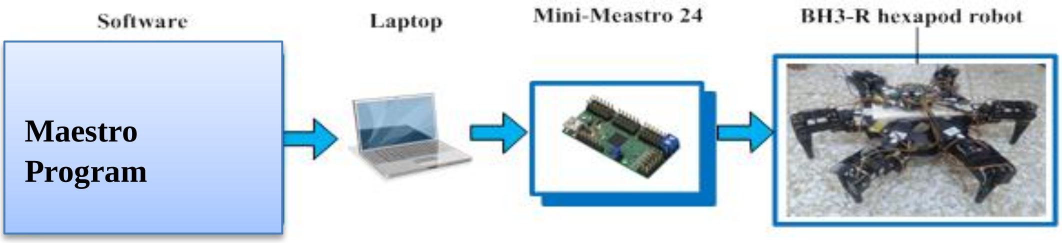


Figure (1): Full experimental work of BH3-R hexapod robot

The all hardware of BH3-R hexapod robot is shown in Figure (2)

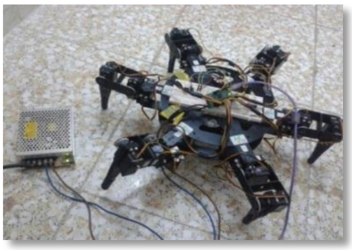


Figure (2): BH3-R hexapod robot of proposed method

4- Hexapod Real Motion

The real motion of all sequences of three gaits is shown in the following figures below:

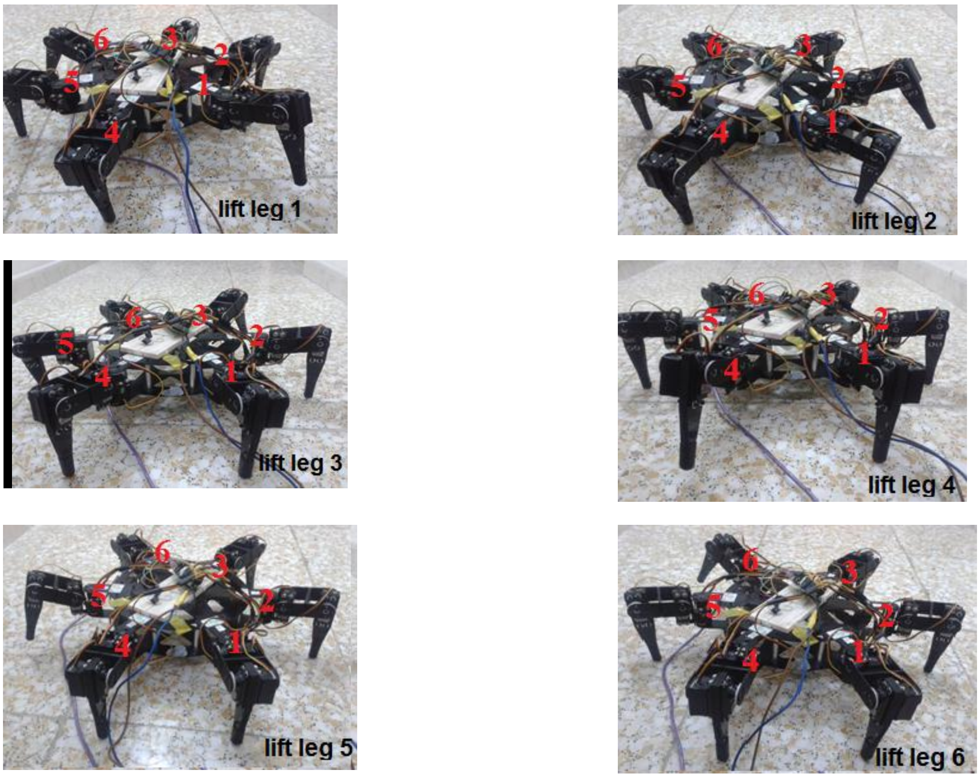


Figure (3): Results of the practical real BH3-R hexapod robot sequences for wave gait

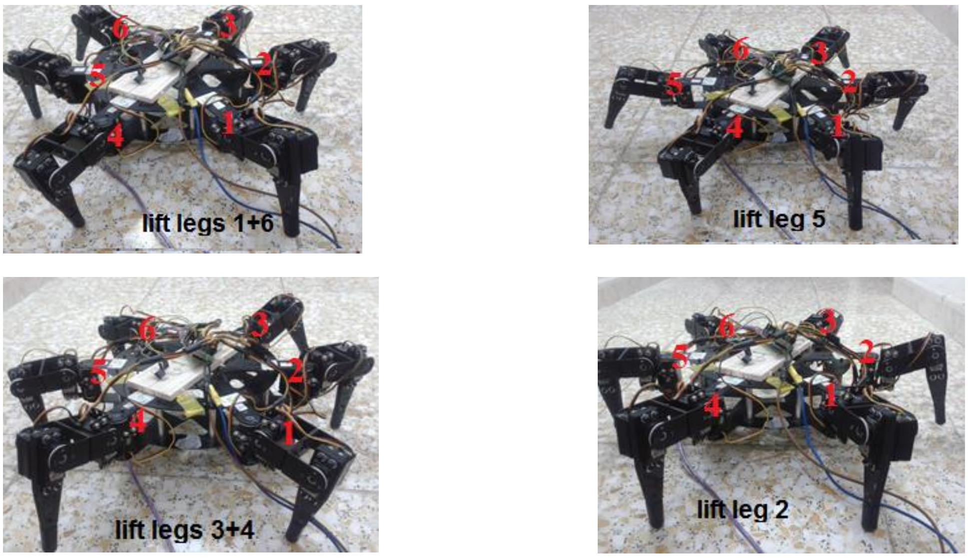
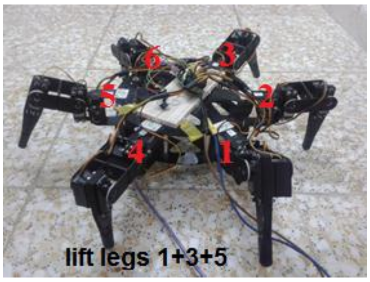


Figure (4): Results of the practical real BH3-R hexapod robot sequences for ripple gait



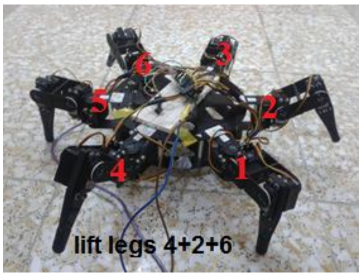


Figure (5): Results of practical real BH3-R hexapod robot sequences for tripod gait

5- Hexapod Path Planning and Stability Margins

The hexapod robot starts walking from the start point of the body center (0, 0) cm to the goal point of the body center (100, 0) cm as an example goal point in real experiment. The results of path planning. For (412) iterations the (x_c) (point of the body center in x-axis), where (e_x = 3.8667 cm) for the ripple gait. After (748) iterations, the error is (e_x = 4.7200 cm) for the wave gait. For the tripod gait the error is (e_x = 2.0000 cm) in (140) iterations (x_c). All coordinates of hexapod legs for coxa, femur and tibia are converted by inverse kinematics into the angles (θ_{i1}, θ_{i2} and θ_{i3}).

The results of coxa angles (θ_{i1}) are ranged between (-20^0, 20^0). The coxa angle is responsible for the movement of the leg either forward (ccw) or backward (cw) movement as shown in Figures (6, 9 and 12).

Besides that, the results of femur (θ_{i2}) are between (0^0, 45^0) that is responsible for the movement of the leg either up or down as shown in Figures (7, 10 and 13). The results of tibia (θ_{i3}) is between (73^0, 91^0) that is responsible for the movement of the leg either up or down as shown in Figures (8, 11 and 14).

The stability margins: the results of best stability margins values in all sequences for each gait of hexapod robot are:

a. In tripod gait, there are two sequences, sm_1 equals to (3.9356) and sm_2 equals to (5.1304).
b. In ripple gait, there are four sequences, sm_1 (6.2614), sm_2 (13.1925), sm_3 (8.4736), and sm_4 (12.5673).
c. In wave gait, there six sequences, sm_1 (6.6121) and sm_2 (13.9895), sm_3 (7.5258), sm_4 (5.4661), sm_5 equals to (12.6927), and sm_6 (6.883).

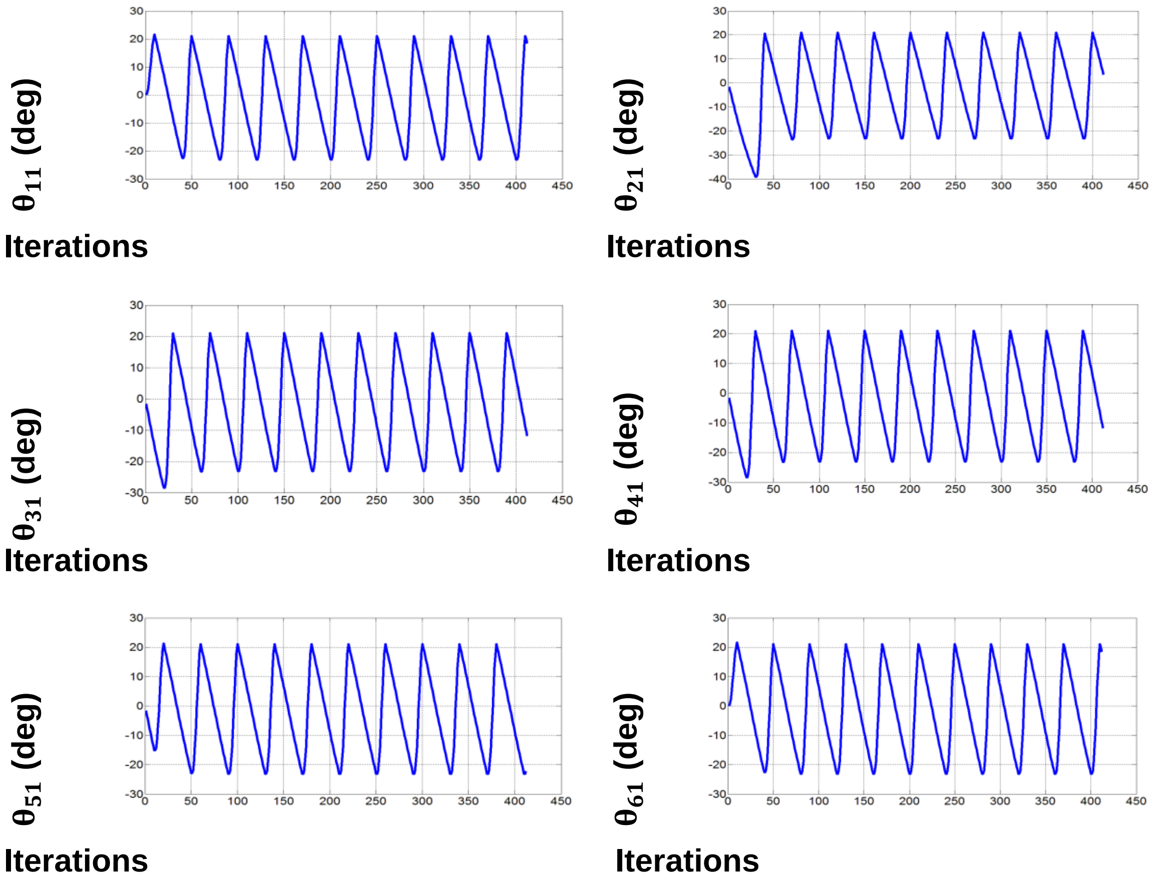


Figure (6): Coxa angles (θ_1) of leg tip for six legs hexapod robot of the ripple gait

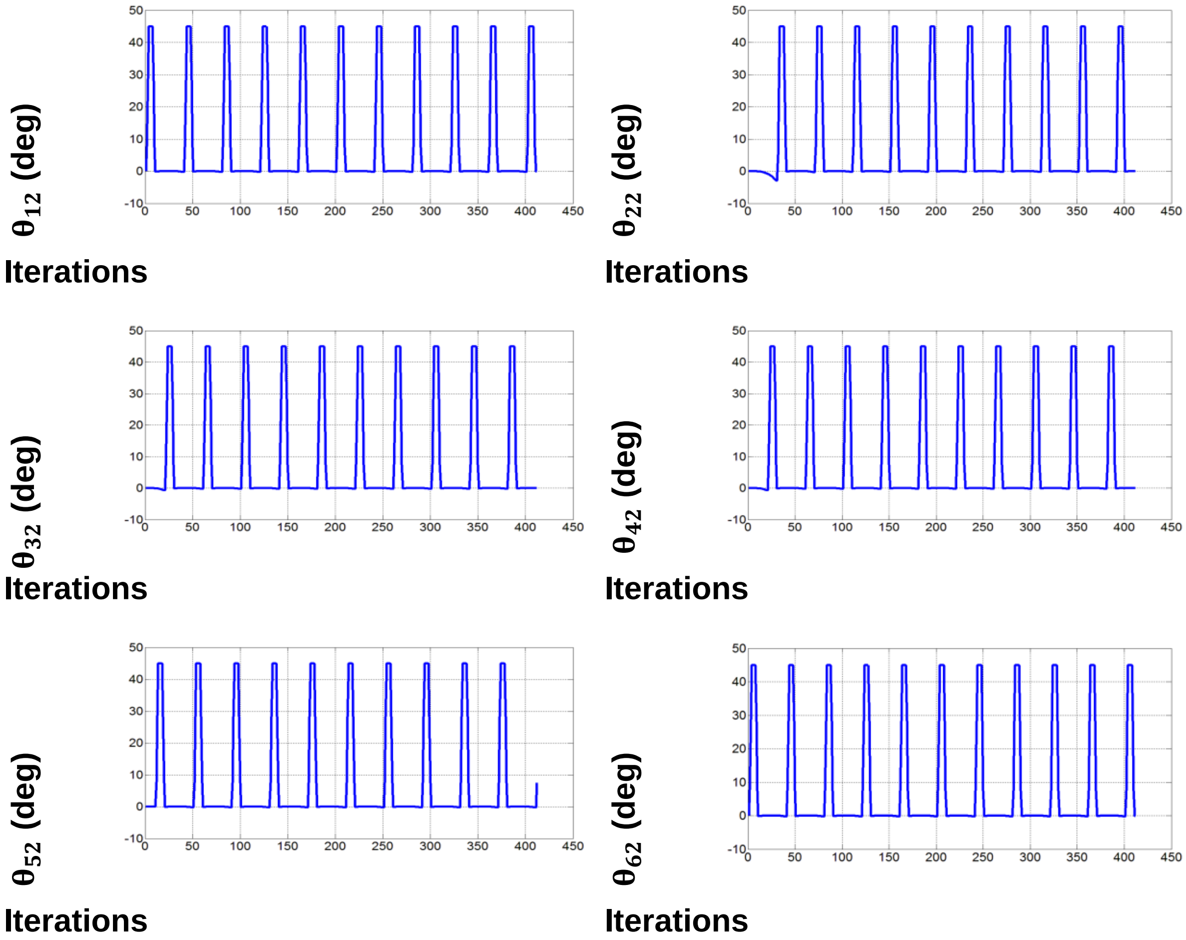


Figure (7): Femur angles (θ_2) of leg tip for six legs hexapod robot of the ripple gait

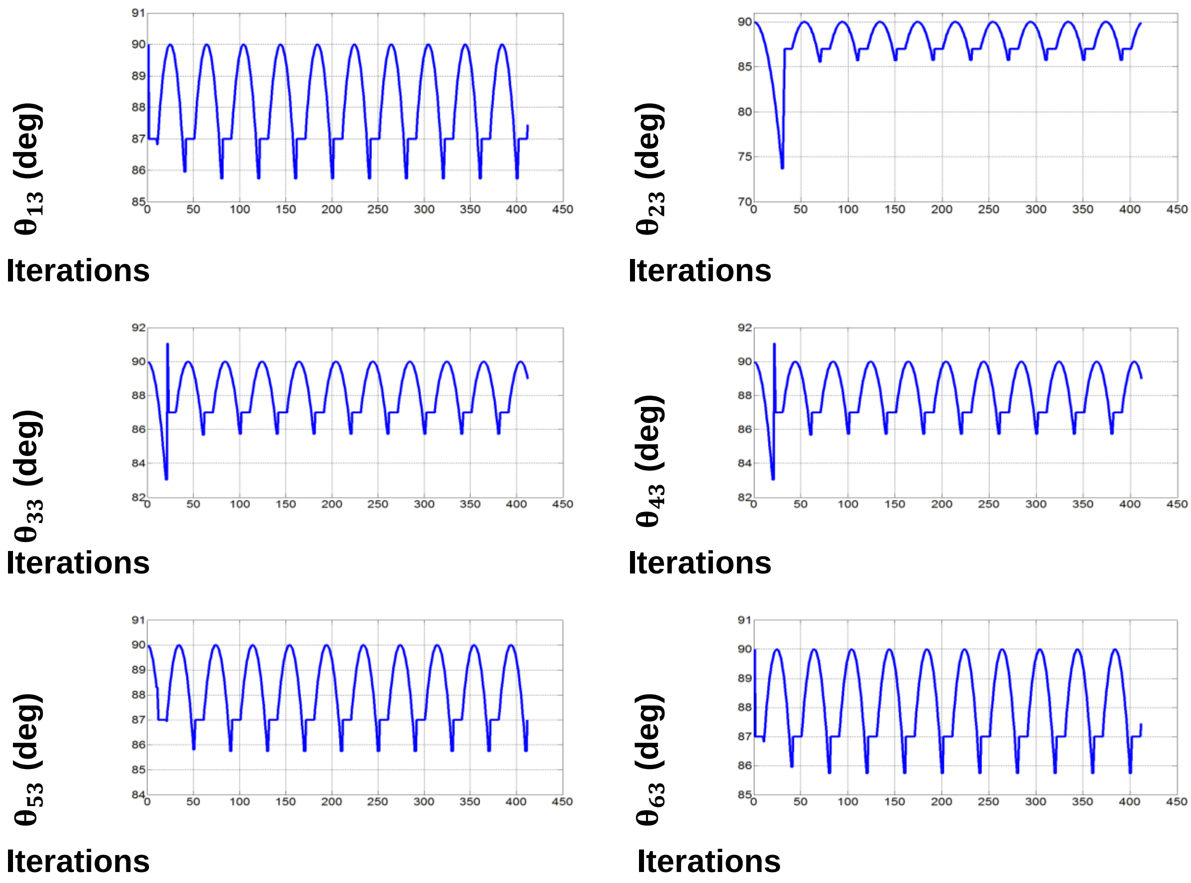


Figure (8): Tibia angles (θ_3) of leg tip for six legs hexapod robot of the ripple gait

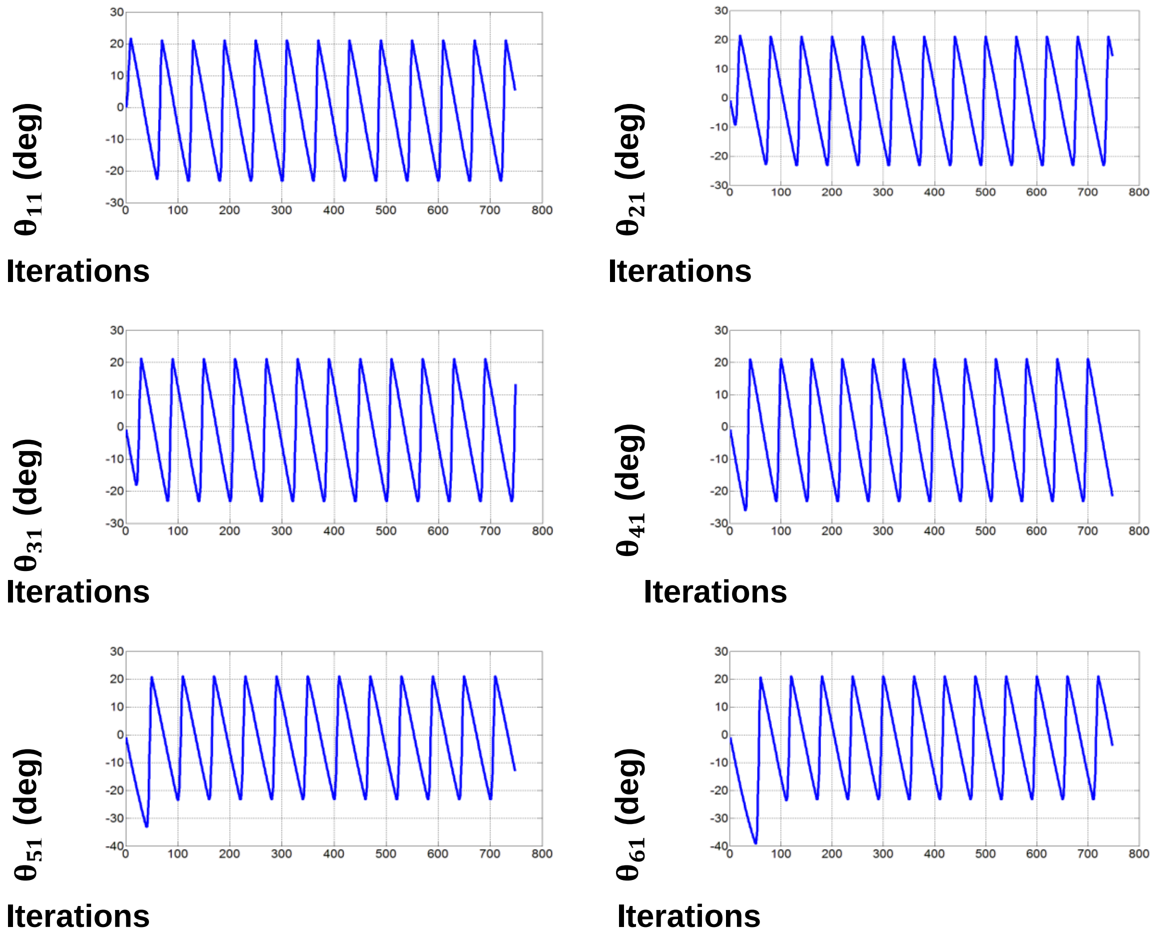


Figure (9): Coxa angles (θ_1) of leg tip for six legs hexapod robot of the wave gait

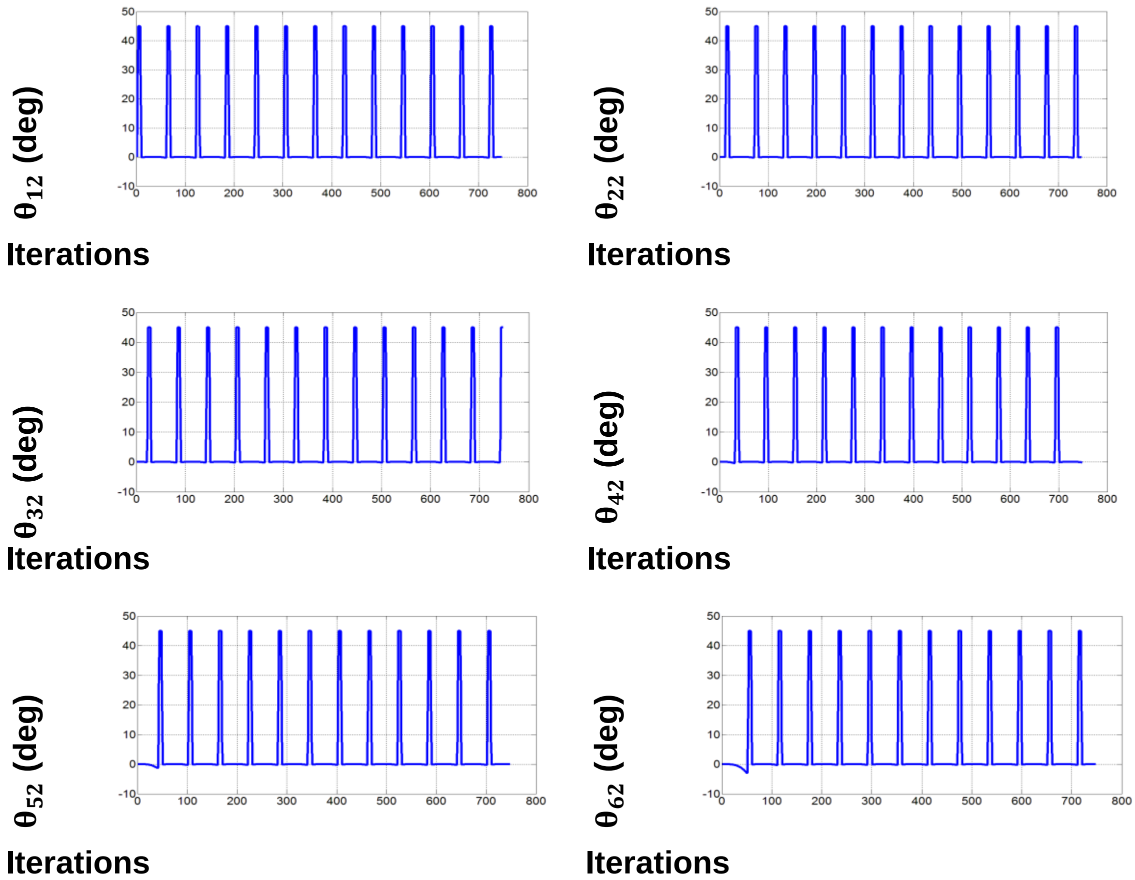


Figure (10): Femur angles (θ_2) of leg tip for six legs hexapod robot of the wave gait

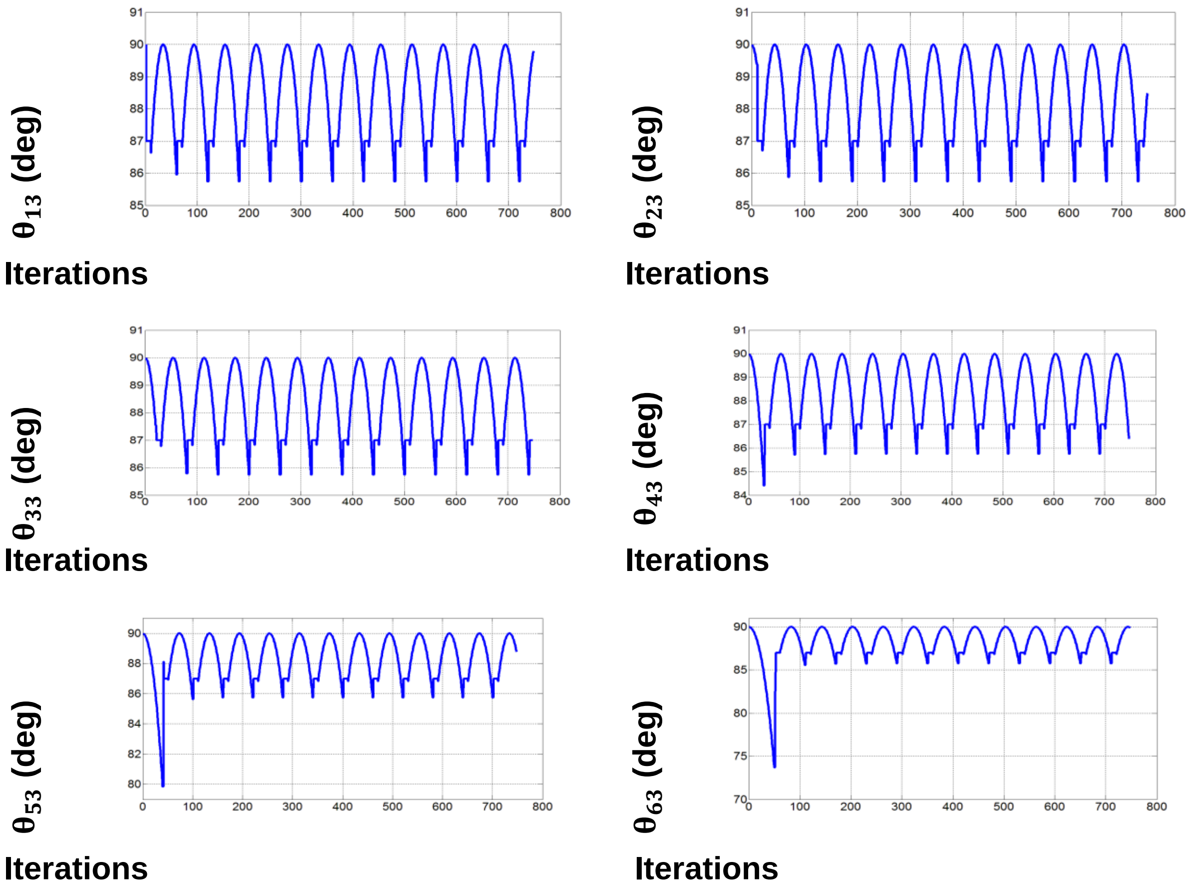


Figure (11): Tibia angles (θ_3) of leg tip for six legs hexapod robot of the wave gait

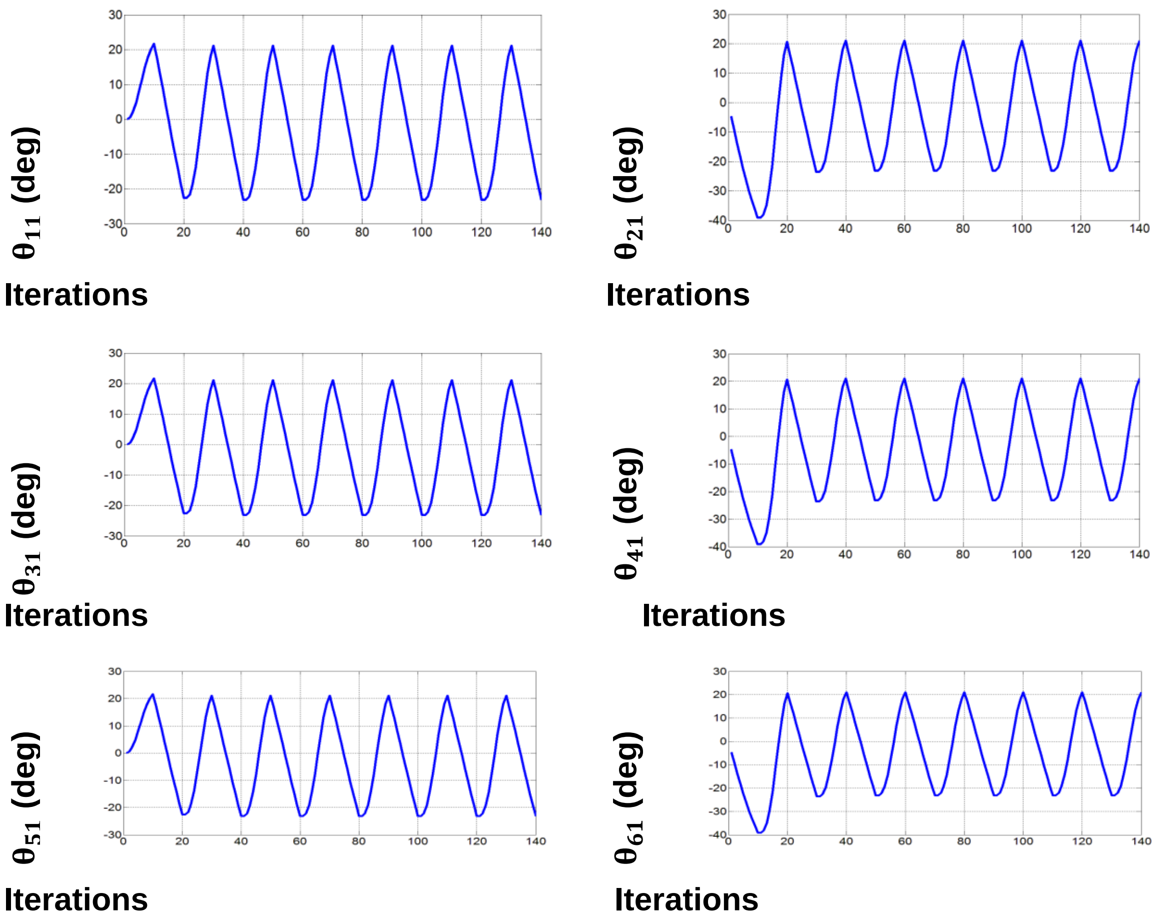


Figure (12): Coxa angles (θ_1) of leg tip for six legs hexapod robot of the tripod gait

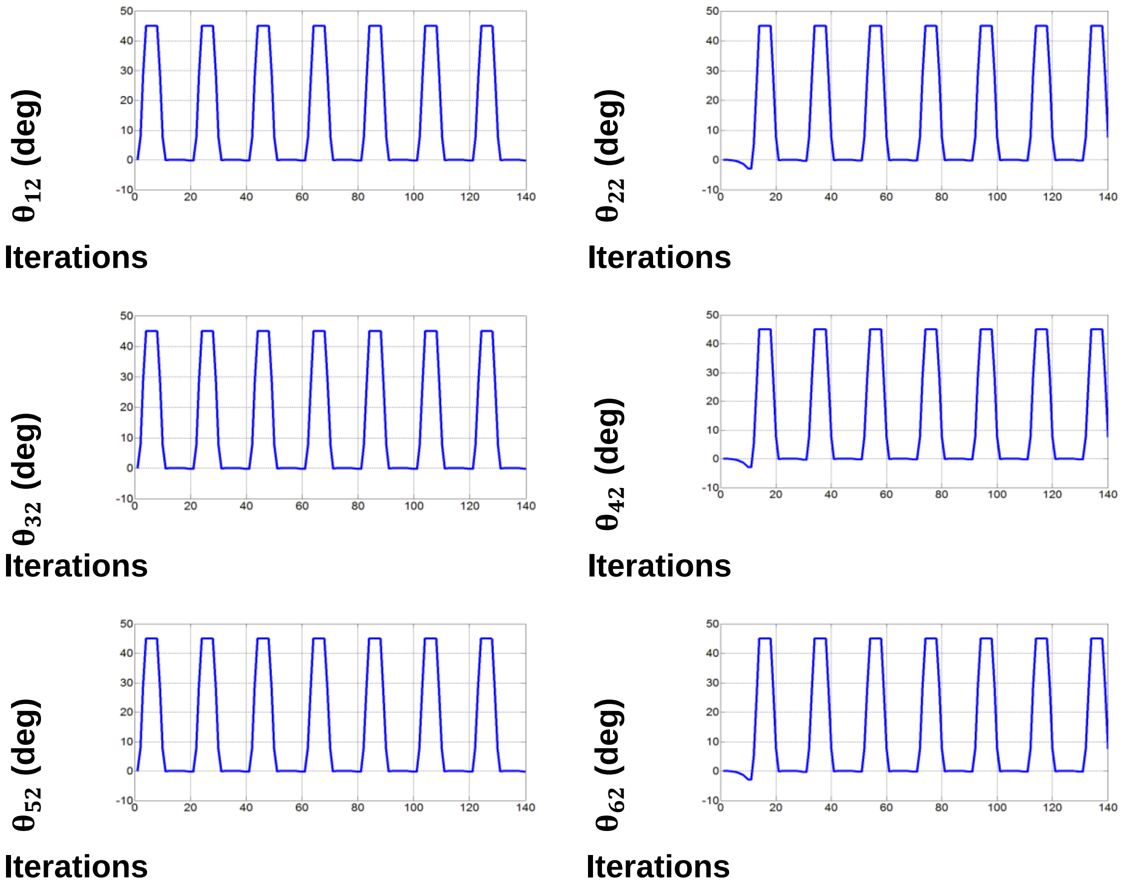


Figure (13): Femur angles (θ_2) of leg tip for six legs hexapod robot of the tripod gait

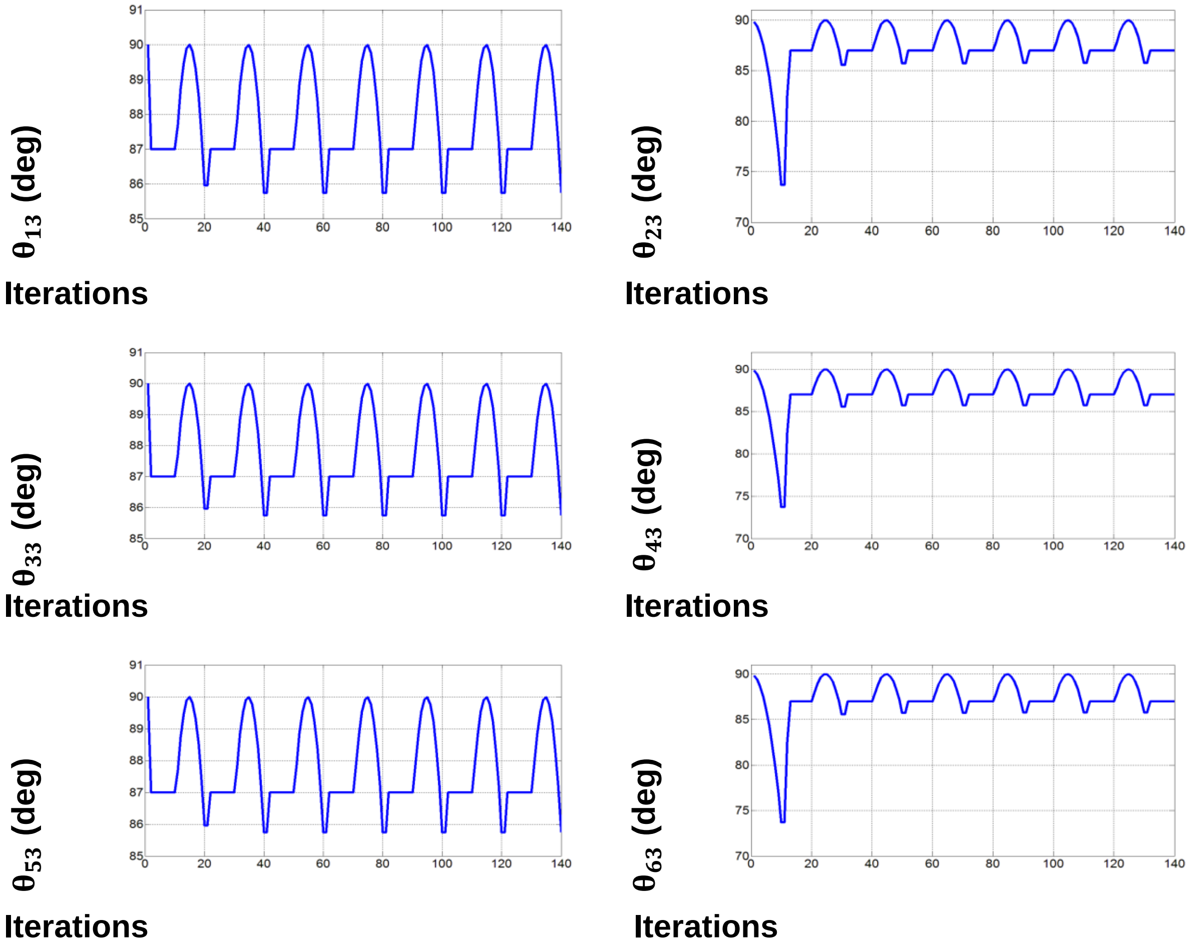


Figure (14): Tibia angles (θ_3) of leg tip for six legs hexapod robot of the tripod gait

Practically the velocities are: wave = 0.416 cm/sec., ripple = 0.7246 cm/sec. and tripod = 0.833 cm/sec.

6- Conclusions

The Real hexapod BH3-R robot has used in this paper. A proposed intelligent method which is (GA) has been applied to find the best static stability using stability margin during each sequence in each gait. Positions of leg's tips are represented in (x_i, y_i, z_i), the results show that these values are within constraints workspace. i.e. (x-axis begin with zero and it is increased till the body center reaches to the goal point of path planning. The y-axis is within constraint workspace, z-axis is ranged (0 cm -

8 cm) according to the swing and stance phases. These values are measured from the leg's tips and converted into the angles.

Angles (joints) of hexapod legs are: coxa angles are ranged (-20^o -20^o), while the femur angles (0^o - 45^o), and tibia angle ranged (73^o-91^o). These values are converted into the PWMs by programming in Maestro applications.

Position errors of path planning begins from start point (0, 0 cm) to the goal point (100, 0 cm) equals to (2 cm) for tripod gait (3.8667 cm) for ripple gait and (4.72 cm) for wave gait. According to the iterations (412 for ripple, 748 for wave, 140 for tripod) and the steps of walking are different velocities that the tripod gait is more velocity than ripple and ripple is more velocity than wave. Practically the velocities are: wave = 0.416 cm/sec., ripple = 0.7246 cm/sec. and tripod = 0.833 cm/sec. The equations of PWM for three joints in each leg are proposed for BH3-R hexapod robot.

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تحليل الاستقرارية الثابتة للهكسابود روبوت باستخدام المحاكاة والعمل التجريبي للخوارزمية الجينية

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BH3-R هكسابود هو روبوت له ستة ارجل للمشي مع جسم دائري الشكل. الهيكل الميكانيكي للهكسابود روبوت يشبه الحشرة لذلك له ثلاث حركات: حركة الموجة، حركة التموج، وحركة الترايبود. المشكلة الرئيسية للهكسابود روبوت هو الحصول على افضل استقرارية ثابتة اثناء حركته. في الطريقة المقترحة تحليل الاستقرارية الثابتة باستخدام الخوارزمية الجينية (GA) حيث تم تنفيذها عملياً لثلاث حركات. وكانت النتيجة الحصول على أفضل الإحداثيات المستقرة لأرجل الهكسابود روبوت (x_i, y_i, z_i) و افضل احداثيات مستقرة لجسم الهكسابود روبوت (x_{ci}, y_{ci}) اعتماداً على افضل اسقرارية ثابتة. في العمل المقترح، تحليل الاستقرارية الثابتة تم استخدامه كمعادلة للخوارزمية الجينية (GA) لكل حركة. نتائج الاستقراريات تم حسابها والهكسابود روبوت تحرك حسب الاحداثيات المستقرة الجديدة للارجل. عملياً فأن سرع حركة الموجة هي الاقل حركة, عندما التموج هي اكثر سرعة من حركة الموجة لكن حركة الترايبود هي الاسرع حركة. الخطأ للمسار الحقيقي لل BH3-R هكسابود روبوت هو قليل للحركات الثلاث. معادلات نبض تعديل العرض (PWM) لثلاثة زوايا مفاصل كل ساق تم اقتراحه عملياً للBH3-R هكسابود روبوت.

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