Planning of motion strategy for hexapod robot using biogeography based optimization Havder Mahdi Abdulridha Hawraa Neema Jasem

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Abstract

The necessity to utilize the usage of the robot cannot be denied since there are a lot of natural disasters occur around the world, the robot can reach places where humans cannot reach. Hexapod robotic is one of the robots utilized in this case due to its balance and versatility at some stage in the movement on any kind of floor. In this project the explanation of using software and hardware Arduino microcontroller is used to control of such a hexapod. The output signal from Arduino for controlling leg's joint angular position such as a pulse called Pulse Width Modulation (PWM). Also Arduino programmed to create the sequence of motion for six legs. The second part of project is about controlling hexapod to avoid hitches and tracking the wall by using PID controller. Tuning of the PID processes based on Biogeography Based Optimization(BBO) need to keep the connection between PC and hexapod, because the BBO was written by Matlab. The experimental results using BBO to optimize the PID controller parameters of hexapod robot show the efficiency of this technique in the adaptation of controller.

Keywords: Kinematics, PID controller, BBO algorithm, The wall tracking.

الخلاصة:

استخدام الروبوت ضرورة لا يمكن انكار فائدتها . لأن هناك كثير من الكوارث الطبيعية التي تحدث حول العالم يمكن للروبوت الوصول الى الأماكن لا يمكن للبشر ان يصل اليها. الروبوت السداسي الأرجل هو احد الروبوتات المستخدمة في مثل تلك الحالات و ذلك لما يتمتع به من الاستقرار يه و المرونة اثناء الحركة على انواع مختلفة من الاسطح. يوضح هذا البحث كيفية استخدام البرامج و اجهزة (Arduino) من اجل التحكم و السيطرة على مثل هكذا نوع من الروبوت سداسي الارجل. الاشارة الصادرة من جهاز (Arduino) للسيطرة على مثل هكذا نوع من الروبوت سداسي الارجل. الاشارة تدعى(تعديل عرض النبضة). كذلك لغة برمجة (Arduino) تمكن من تتسيق حركة الارجل الستة الحدورة عدي (تعديل عرض النبضة). كذلك لغة برمجة (Arduino) تمكن من تتسيق حركة الارجل الستة المادرة من جهاز (Arduino) للسيطرة على موقع الزاوي لمفاصل الساق و التي تكون على شكل نبضة تدعى (تعديل عرض النبضة). كذلك لغة برمجة (Arduino) تمكن من تتسيق حركة الارجل الستة الموبوت. الجزء الثاني من البحث يكمن في كيفية تجنب العقبات و تتبع الجدار من خلال استخدام وحدة في ضبط خوارزمية السيطرة على الروبوت و التقليل من اخطاء التتبع التي يمكن الاعتماد عليها التحكم (النسبي, التكامل, المشتقة). لقد اثبتنا في بحثنا هذا ان الخوارزمية التطورية يمكن الاعتماد عليها التحكم (النسبي التكامل, المشتقة). لقد اثبتنا في بحثنا هذا ان الخوارزمية التورية يمكن الاعتماد عليها التحكم (النسبي التكامل, المشتقة). لقد اثبتنا في بحثنا هذا ان الخوارزمية التورية يمكن الاعتماد عليها في ضبط خوارزمية لسيطرة على الروبوت و التقليل من اخطاء التتبع التي يمكن ان تحدث. يتم استخدام في ضبط خوارزمية العيورية اليوريا على الروبوت المقليل من اخطاء التتبع التي يمكن الاعتماد عليها الاتصار التسليمية العربية الميرة على الروبوت و التقليل من اخطاء التنبع من المورزمية الخرافي. تكيف الجغرافي المي المناسام السيور على المالمان المنام ال التسليم عرب المور المي الجرافي. تكيف الجغرافية الحيوية تلمي الروبوت سام ال المالي التجربية باستخدام نظرية تكيف الجغرافي. الحيوية لتصين معالم نظام التحكم لروبوت ساداسي الأرجل تظهر ركفاءة هذه التقنية في التكيف مع وحدة تحكم الحيوية الحيوية المام التحكم لروبوت ماداسي الأرجل تظهر ركفاءة هذه التوني مالغي ال

الكلمات المفتاحية : الكينماتيكا ، تحكم PID، خوارزمية BBO، تتبع الجدار .

1. Introduction

Robot field is a comparatively new area in modernism technology (Mark *et.al.*, 2004). The most suitable choice for the mobile Robots according to the terrain is unsuitable and over highly fracture is legged robots(Uluc, 2002). The leg, which consists of number of degrees of freedom, should be able to carry portion of weight of the robot, and should be able of rising and dropping the robot(Roland and Illah, 2004). Definition of the hexapod robot has six legs with the mechanical structure design, way of movement and the motion of the legs and walking of hexapod robot inspired by insects and ants or other bugs(Ying *et.al.*, 2012).

Movement with legs is a suitable state for motion on baggy-tough-irregular lands. Control of the legged can supply effective orders, where used isolated footholds in this robots which lacks in tracked and wheeled systems. The robot can be walked to a required direction, for instance in forward direction, despite to the differences in the type of lands. The most beneficial of robot with legs is small harm or not effect to the land. It contains complex concept for kinematics and dynamics of the leg and also large number of actuators should control them to maintain the continuity and coordination of movement; so, controlling of this kind of locomotion is very hard in compare to another locomotion systems(Mustafa, 2006).

2. Modelling of Hexapod Robot

The movement of legged robot verities by means of verity of normal terrain and it gives a set of hard troubles (leg position, hitches avoidance, division of the load and balance) which must focus in the field of both in mechanical creation of motors and in improvement of controller (Krzysztof *et.al.*, 2008). Every leg in hexapod has three successive parts. The first link coxa is attached to the frame, the second link femur is attached to the coxa and the third link tibia is attached to the femur, every via a servomotor moved the joint that is giving each leg three Degree Of Freedom(DOF). Total degree of freedom for hexapod robot is 18-DOF as shown in figure(1). Figure(2) shows legs number and joints tagging. Also joints rotation axis are shown where joint2 and joint3 rotation axes are perpendicular to the screen (comes out of screen). The green arrows indicate that coxa, femur and tibia rotate around their respective rotation axes.



Figure (1) Hexapod robot



Figure (2) Hexapod top view and rotation axes

The center of hexapod is at (0, 0, h) where h is the perpendicular height of the center of hexapod from the ground. These coordinates change during the robot locomotion. The z-axis pointing up, the x-axis pointing right and the y-axis pointing forward. Modelling of the hexapod which includes kinds, first is front kinematic and second is opposite kinematic , beneath will talk in information for each kind of kinematic:

2.1. Forward kinematics for One Leg of hexapod robot

The forward kinematics trouble explains the relation between the robot joints and the location and direction for the end effector of the foot (Mohammad, 2013). There are three joints in each leg named according to site where symbolized by $(\theta_c, \theta_f, \theta_t)$ rotational type as shown in figure(3). it should utilize "Denavit Hartenberg convention" for one leg kinematics because hexapod consists of symmetrical body with six similar feet (Umar, 2012).



Figure (3) Kinematic model of one leg

The lengths of the hexapod's leg are: coxa link ($L_c=29mm$), femur link($L_f=85mm$), tibia link ($L_t=125$ mm).

The main homogenous transformation matrix (A_i) that relate link i-1 with link i is given by Eq.(1) and it can be used to find the homogeneous transformation matrix for each link. Parameters acquired through the application of the D-H procedure are offered in Table (1) (Umar, 2012).

Where;

 θ_i (Joint offset) is edge between X_{i-1} and X_i along Z_{i-1}

 a_i (Link length) is distance between Z_{i-1} and Z_i along X_i

 d_i (Link offset) is distance between X_{i-1} and X_i along Z_{i-1}

 \propto_i (Link twist) is edge between Z_{i-1} and Z_i along X_i

i= number of links

Table (1) Denavit fiai tenderg parameters of the robot nexapou				
Ι	\propto_{i}	θ _i	a _i	d _i
0	0	0	0	0
1	90	θ_{c}	l _c	0
2	0	θ_{f}	l_{f}	0
3	0	θ_{t}	l _t	0

Table (1) Danavit Hartanharg naramatars of the report havened

$$A_{i} = \begin{bmatrix} \cos \theta_{i} & -\sin \theta_{i} \cos \alpha_{i} & \sin \theta_{i} \sin \alpha_{i} & a_{i} \cos \theta_{i} \\ \sin \theta_{i} & \cos \theta_{i} \cos \alpha_{i} & -\cos \theta_{i} \sin \alpha_{i} & a_{i} \sin \theta_{i} \\ 0 & \sin \alpha_{i} & \cos \alpha_{i} & d_{i} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
(1)

The refer on of the matrix that represent the total transformation of the position and orientation for the end of the foot expressed in base coordinates is shown in Eq.(2).

$$T_t^0 = A_c^0 \times A_f^c \times A_t^f$$
⁽²⁾

Considering Fig.(3) and by using Eq. (2) the coordinates of the leg tip are:

$$\begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} = \begin{bmatrix} \cos\theta_c (L_c + L_t \cos\theta_{f+t} + L_f \cos\theta_f) \\ \sin\theta_c (L_c + L_t \cos\theta_{f+t} + L_f \cos\theta_f) \\ L_t \sin\theta_{f+t} + L_f \sin\theta_f \end{bmatrix}$$
(3)

For getting the location the end of the foot with respect to hexapod movement centroid, it must be taken to consideration the body rotations in 3D-space. Body rotations (Roll-Pitch-Yaw) shows by Eq. (4).

$$\begin{cases} \text{Roll} = \text{Sigma}(\sigma) = \text{Bady Rotation about } X - \text{axis}, R_{x,\sigma} \\ \text{Yaw} = \text{Gamma}(\gamma) = \text{Bady Rotation about } Z - \text{axis}, R_{z,\gamma} \\ \text{Pith} = \text{Phi}(\emptyset) = \text{Bady Rotation about } Y - \text{axis}, R_{y,\emptyset} \end{cases}$$

$$Ft = R_{x,\sigma} \times R_{y,\emptyset} \times R_{z,\gamma}$$
(4)

 $\begin{bmatrix} Ft_x \\ Ft_y \\ Ft_z \end{bmatrix} = \begin{bmatrix} T_z \sin \phi + T_x \cos \phi \cos \gamma - T_y \cos \phi \sin \gamma \\ T_x (\cos \sigma \sin \gamma - \cos \gamma \sin \phi \sin \sigma) + T_y (\cos \gamma \cos \sigma + \sin \gamma \sin \phi \sin \sigma) - T_z \sin \phi \sin \sigma \\ T_x (\sin \gamma \sin \sigma - \cos \gamma \cos \sigma \sin \phi) + T_y (\cos \gamma \sin \sigma + \cos \sigma \sin \gamma \sin \phi) + T_z \cos \phi \cos \sigma \end{bmatrix}$ (5) **2.2. Inverse kinematics**

The opposite kinematics troubles are conversely the forward kinematics trouble, which wills finding the joint variables values from a wanted location and direction for the end effector of the foot [Mohammad, 2013]. The total homogenous transformation formula is needed for a leg in 3D-space given by Eq.(2) as in Eq.'s(6) & (7).

$$\begin{aligned} &\text{inv}(A_{c}^{c}) \times T_{t}^{0} = A_{f}^{c} \times A_{t}^{t} \end{aligned} \tag{6} \\ &\text{inv}(A_{f}^{c}) \times \text{inv}(A_{c}^{0}) \times T_{t}^{0} = A_{t}^{f} \end{aligned} \tag{7} \\ &\text{Where;} \quad T_{t}^{0} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & P_{x} \\ r_{21} & r_{22} & r_{23} & P_{y} \\ r_{31} & r_{32} & r_{33} & P_{z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{aligned}$$

Solving (6) then Compare r_{34} values in both sides, you can find θ_c angle as in Eq. (8).

$$\theta_{\rm c} = \tan^{-1}(\mathbf{P}_{\rm y}, \mathbf{P}_{\rm x}) \tag{8}$$

Solving Eq.(7), you can find θ_f angle as in Eq. (9) and also obtaining θ_t angle as in Eq. (10)(Umar, 2012).

$$\cos \theta_{\rm f} = \tan^{-1}(P_{\rm z}, D) + \left(\left(\sqrt{D^2 + P_{\rm z}^2 - G^2} \right), G \right) \tag{9}$$

Where; $D = P_x \cos \theta_c - L_c + P_y \sin \theta_c$ and $G = \frac{(D^2 + L_f^2 + P_z^2 - L_t^2)}{2 \times L_f}$ $\theta_t = \tan^{-1} ((P_z \cos \theta_f - \sin \theta_f \times D), (\cos \theta_f \times D - L_f + P_z \sin \theta_f))$ (10) **3. Leg constraints**

The size of the parts coxa, femur and tibia are not flexible for the hexapod. Because of this each leg will not reach longer than these parts combined. Practically,

Because of this each leg will not reach longer than these parts combined. Practically, this will create a sphere with a certain radius around the coxa rotation center that is accessible space for the leg for every height this means, there will be two circles around the coxa rotation point representing the outer and inner bound for the legs to be able to positioned in. Figure (4) refers to a graphical representation of the constraints.So, a calculation of r1 and r2 radius are needed to find the restricted space While taking body-coxa joint angle (θ_c) as the border to draw circles.



Figure (4) Each leg has its own restricted space where it is allowed to move in. It is restricted by an inner (r1) and outer (r2) boundary.

As is seen in figure (4), the areas of possible leg positions are overlapped. This will introduce another problem because legs might bump into each other. A way of reducing these risks the legs have an additional constraint by limit the body-coxa angle to ($\theta_c = \pm 12$) (Dan and Sebastian, 2015).

4. PID Controller

More control algorithm that used to control the robot is a proportional-integralderivative (PID) controller, PID use three factors (Kp, Ki, Kd) to determine what controller to do for the robot. PID controller is continuous time mathematically as shown in Eq. (11) (Visioli, 2001):

$$u(t) = K_{p} e(t) + K_{i} \int_{0}^{t} e(t)dt + K_{d} \frac{de(t)}{dt}$$
(11)

In this paper, the distance from the side wall is controlled by using PID controller. The error results from the different between desired and output signal minimized or removed depends on the three parameters, as seen in figure (5).



Figure (5) Close loop system of wall following

Figure (5) showed all system for the wall tracking hexapod. Desired distance is input signal to the system. Two ultrasonic sensors (USs) is used in side of hexapod to supply the feedback signal (measured value) by reading amount of distance from wall. The error will be calculated and treated during limited maximum and minimum angle of turning for body-coxa joint's motor in leg2 and leg5.

5. Biogeography Based Optimization(BBO)

Biogeography based optimization (BBO) is an evolutionary algorithm that depended on the notion of biogeography of the isle and that explains the factors that lead to the type's richness of secluded natural societies (Devin and Robert, 1999).Transmigration divided in two essentially processes immigration and emigration. They are influenced by different factors for example the isle extent, the isle the neighbor and Habitat remoteness between the and Suitability Index (HSI). Where HSI includes different factors for example plants, rainfall, weather etc. These factors favor the presence of types in a habitat. High HSI is habitats contain many of types, so will be having few rate of immigration and rise rate of emigration. Similarly, Low HSI is habitats contain little number of types. In BBO used this concept for carrying out migration, where they begin to establish a great number of nominee solutions to a particular problem. HSI associated with each solution represent as a homeland and every solution or homeland is a set of Suitability Index Variables (SIVs). SIVs marked the appropriateness of the homeland to which it belongs .when "HSI" is high the homeland represent as perfect solution and when HSI is low the habitat represent as bad solution. Relationship of all concepts (number of types, immigration rate and emigration rate) gives as a figure (6) (Arora et.al., 2012).



Figure (6) the relation for (number of types, immigration rate and emigration rate)

I : the max. immigration rate.

E : the max. emigration rate.

 S_0 : the balance number of types

 $S_{\mbox{max}}$: the max. number of types .

 λ_s is the immigration rate and μ_s is emigration rate. For the line migration rates of figure (6), you can get Eq.'s as seen in (12)&(13).

$$\mu = ES/S_{max}$$
(12)

$$\lambda = I \left(1 - \frac{S}{S_{\text{max}}} \right) \tag{13}$$

In order to model the concepts of BBO in detail, The island contains S types. The probability P_s varied from time t to $(t + \Delta t)$ as shown in Eq. (14): (Arora *et.al.*, 2012)

 $P_{s}(t + \Delta t) = P_{s}(t)(1 - \lambda_{s}\Delta t) + P_{s-1}(t)\lambda_{s-1}\Delta t + P_{s+1}(t)\mu_{s+1}\Delta t$ (14) **6. hexapod robot Walk and wall tracking :**

The method for walking and wall following of hexapod robot are explained in this section :

6.1. Tripod gait analysis

To execute gait, each leg will have a stand phase and a swing phase. It must be the work of the swing phase by the leg away from the earth and move forward then come down to earth in the new site. The condition for a swing phase is that has a beginning point and an ending point on the earth (See Figure (7) - A and C positions). once you determine the end point in the program the robot leg will not guarantee moving away from the earth, so the purpose was not achieved. Therefore they developed intermediate point placed to solve this problem (See Figure (7) - B position). It is better to make swing phase synchronously with the time of the stance phase. The legs on group 2 in stance phase must stay on the ground by moved backward respect to body-coxa joint and in turn, will push the body forward (Shalutha, 2014).



Figure (7) Positions of swing phase for one leg. Swing phase starts at A, The intermediate position is B (off the ground) and ends at leg being landed at position C.

Make hexapod robot walks entirely, every time you deal with three legs as group when first group finished path(swing phase), exchanged to second group of legs according to way of walking. The legs of hexapod are divided to: the first group consisting of 2,4,6 legs, and second group consisting of 1,3,5 legs. To allow the

hexapod to turn, by decreasing/increasing step length, one side will move slower/faster and thus allow for turning.

For each of the joints in a leg there are four different state target positions which make the hexapod walk forward. These positions are listed in table (2).

Table (2) Target joint angles for the legs						
Phase	Joint 1	Joint 2	Joint 3			
Swing phase-START	-12	-20	-20			
Swing phase- END	12	-20	-20			
Stance phase – START	12	-20	-20			
Stance phase – END	-12	-20	-20			

Table (2) Transitions are fisted in table

6.2. Wall tracking for six-legged robot

The purpose of the robot controller is to maintain specific distance from the wall. Here, the angle (θ_{wall}) between the robot orientation and the wall orientation is calculated. Based on figure(8)(Paul *et.al.*, 2011).

$$X = DFr - DBr$$

$$\theta_{\text{wall}} = \operatorname{atan}\left(\frac{X}{(LFr+LBr)}\right) \tag{16}$$

This gives an angle which tells the hexapod robot which way it is moving, so: $\theta_{wall} = \theta_{turning}$

(15)

(17)

The tracking error is calculated as:

 $e(t) = y_{ref} - y$

Where; DFr: distance between right front sensor and wall

DBr: distance between right back sensor and wall

LFr: distance between center of right front sensor and center of robot LBr: distance between center of right back sensor and center of robot

 y_{ref} : distance between reference path and wall

y: distance between oscillation path and wall



Figure (8) Connection between robot position and wall

7. Experimental Results

7.1. Results of walking strategy

The first implemented controller was a hard-coded locomotion pattern that allowed for walking straight. The result of the operation of the servomotor in bodycoxa joint experimentally illustrate in the drawing (9) for two cycles. The job of leg explains as angular position ,start with body-coxa joint's motor for legs (1,3,5) is moving by -12 to+12 degree from 90 (reference angle) to gives transfer phase for joint1from 78 to 102 degree at rising time in figure and it is moving by +12 to -12degree from 90(reference angle) to gives stance phase for joint1from 102 to 78 degree at dropping time. Vice versa for legs(2,4,6) because it depend on direction of each motor to push robot toward forward direction.



Figure (9) output signal for body-coxa joint's motor, sample time t= 8ms and delay time T=100ms.

As soon as the group1 starts the swing phase, the group2 starts the stance phase as shown in figure(10) for making robot more flexible and continuous during motion. The time for one step of the hexapod robot equal to 4.6 sec. Also you can find the maximum and the minimum speed of the hexapod as ds/dt that equal to 0.01 to 0.016 m/s, where s1=4.662 cm and s2=7.518 cm.



Figure (10) output signals for two body-coxa joint's motors for group1 &group 2, sample time t= 8ms and delay time T=100ms.

The motor in femur-tibia joint is the same angular position of coxa-femur joint's motor. Figure (11) shows the transfer phase and stance phase operation for joint 2 &3 with respect to joint 1.we can see the longest time for leg trajectory is equal to16ms, it is the best value for preventing overshoot, so the leg moves smoothly.



Figure (11) output signals for body-coxa joint's motor at leg6 is B and coxafemur joint's motor at leg6 is A, sample time t= 8ms and delay time T=100ms

The complete forward tripod motion for hexapod shown in figure(12), it show that each 3legs in group work together. The cycle begin with femur and tibia link up then during delay time the coxa link start to operation then femur and tibia are go down and return the coxa link to initial position at last. It represent theoretical of motion for robot where the experimental results are identical to theoretical programing



Figure (12) Walk of hexapod

The difference between turn (right or left) and forward motion in body-coxa joint's motors direction only.

7.2. PID controller results

Experimentaly, in this project the limits of the value of X is considered from{-3cm to 3cm} for finding the amount of $\theta_{turning}$ as output from PID controller.

If X=0 the hexapod moved forward where robot parallel to wall,when X>0 the hexapod turn right by changes the angle of the body-coxa joint motor for leg 2. But when X<0 the hexapod turn left by changes the angle of the body-coxa joint motor for leg 5. The important conditions for moving hexapod forward are wall ultrasonic sensors DFr&DBr > 30 cm or DFr&DBr < 40cm. The distance < 30cm is neglected to cancel the effect of legs and also the distance > 40cm for removing another objects effect. After several testes the best values for Kp, Ki, Kd by manual method is shown in figure (13).





You can understand the results of manual way by grasping ideal values for the amount of rotation angle for each value of X. If X=1 to 1.9 cm takes the $\theta_{turning}$ = 7 to 13 degree, for X=2 to 2.9 cm takes the $\theta_{turning}$ = 14 to 20 degree and for X=3 to 3.9 cm takes the $\theta_{turning}$ = 21 to 26 degree as a best value. The X values represented by the input signal are offset by the $\theta_{turning}$ values in the output signal.the positive part represents the right direction of the robot and the negative part represents the left direction of the robot. The response and the accuracy of the robot are better and error is less compared with other values of the PID parameters .This method is more difficult, it needs more experimental test and changes parameters values.

7.3. PID parameters result from BBO

The PID parameters are given from BBO algorithm ,when tuning Kp after 55 iteration the value is equal to7, as shown in figure (14).



Figure (14) BBO's performance in the proof of best Kp= 7 And when tuning Ki, you can find after 46 iteration the value is equal to1.5 as shown in figure (15).



Figure (15) BBO's performance in the proof of best Ki= 1.5

Finally, when tuning Kd, you can find after 22 iteration the value is equal to 0.75 as shown in figure (16).



Figure (16) BBO's performance in the proof of best Kd= 0.75

After used the results of BBO algorithm for tuning PID parameters you can find the input and output signal in figure (17).



Figure (17) output and input signal to PID ,*kp*=7,*Ki*=1.5,*kd*=0.75,time=30 sec

Figure(17) appears tuning PID parameters with BBO is effective and excellent for finding optimize value and don't need several change as we do in manual experiment, it automatically find perfect values after running it.

8. Conclusions

This paper highlights on the development of a controller of the robot. This work was needed extensive knowledge of many sciences in engineering because of the wide domain in robotics field. The following points can be understand from the outcomes acquired in this job:

- 1. The hexapod robot designed from 6 legs and each leg consists of 3 DOF to permit for best locomotion and extraordinary extent of motion. To make the robot moves independently, the (ultrasonic sensors) is used to detect and lack of collision the robot with wall and avoid hitches.
- **2.** The best way for walking hexapod robot on even lands is the tripod motion, and the designs achieved this goal.
- **3.** This job has succeeded in used BBO algorithm for path planning of the wall following. The results give in the ability of tuning the PID control parameters with used BBO algorithm .So hexapod robot can followed the wall with optimize values for parameters which they get from BBO.

Reference

- Arora P., Kundra H., Panchal V., 2012, "Fusion of Biogeography Based Optimization and Artificial Bee colony for Identification of Natural Terrain Features", International Journal of Advanced Computer Science and Applications, Vol. 3, Pp. 107-111.
- Dan T. and Sebastian S. , 2015," Motion Control of Hexapod Robot Using Model-Based Design", MSc Thesis, Department of Automatic Control, Lund University, Printed in Sweden.Pp.
- Devin L. and Robert J., 1999," Many-Legged Maneuverability : Dynamics of Turning in Hexapods", University of California, Berkeley, Printed in Great Britain, Pp. 1603–1623.
- Krzysztof W., Dominik B. and Andrzej K., 1999, "Control an environment sensing system for a six-legged robot,", Journal of Automation, Mobile Robotics & Intelligent Systems, Vol 2, No. 3, 2008.
- Mark W., Seth H. and M. Vidyasagar ,(28 January 2004)," Robot Dynamics and Control ", 2nd Edition.Pp.
- Mustafa S., 2006, "Six-Legged Walking Machine: The Robot-EA308", Ph.D. Thesis ,Middle East Technical University, 157 pages.
- Mohammad M., 2013, "Analytical Workspace, Kinematics, and Foot Force Based Stability of Hexapod Walking Robots", Ph.D. Thesis, Worcester Polytechnic Institute.Pp.
- Paul L., George T., and Dan S., 2011., "Biogeography-Based Optimization for Robot Controller Tuning ", Cleveland State University, Cleveland, Ohio, USA,Pp.
- Roland S. and Illah R., 2004," Introduction to Autonomous Mobile Robots", Library of Congress Cataloging-in-Publication Data, Massachusetts Institute of Technology.Pp.
- Shalutha De Silva, "Force Controlled Hexapod Walking", Ph.D. Thesis, Queensland University of Technology, 2014.Pp.
- Uluc S., 2002, "Dynamic Locomotion with a Hexapod Robot", Dr. Thesis, University of Michigan.Pp.
- Umar A. ,2012," Virtual Reality to Simulate Adaptive Walking in Unstructured Terrains for Multi-Legged Robots", National University of Sciences & Technology (NUST), Pakistan.Pp.
- Visioli A., "Tuning of PID Controllers with Fuzzy Logic", IEEE Proceedings Control Theory and Applications. Vol. 148, No. 1, Pp. 1-8, 2001.
- Ying L., Paul M. and Joe C. , 2012," Autonomous Hexapod Robot Final Report", University of Victoria.