Biologically Inspired Self-Reconfigurable Hexapod with Adaptive Locomotion

Ammar Akhlaq
101519024@umt.edu.pk

Ayesha Umber
Department of Electrical Engineering
University of Management and Technology
Lahore 54007, Pakistan

Jameel Ahmad
Jameel.ahmad@umt.edu.pk

Abstract— **This paper describes the implementation of biologically inspired self-reconfigurable control system for a multivariable hexapod robot having gait switching ability. It focuses on the control; based on forward and inverse kinematics for systematic locomotion and navigation of robot. Electronic system have the capabilities to measure physical variables. Force and pressure sensors are mounted on each end of the leg to provide the necessary sense of touch. The paper also explains the reconfiguration ability of the robot in case of any damage to its leg and its capacity to change the walking pattern according to the malfunction caused. The system implementation using multiple microcontrollers in master-slave configuration to produce and control 18 DOF is also shown in the paper.**

***Keywords*— Hexapod robot, 18 DOF motion, biologically inspired robot, multiple gait robot, navigation of hexapod, kinematics and inverse kinematics for hexapod**

I. INTRODUCTION

Mother Nature has figured out many magical combinations to produce effective, efficient and perfect processes. After nearly 3.6 million years of evolution nature has transformed itself into an ideal, flawless and immaculate system. Due to its indefectibility human engineers and designers are continuously imitating nature to solve their complex problems. Biomimetic is providing the path to produce more accurate and efficacious devices [1].

Arthropods are best candidates for imitation because of their jointed appendages, exoskeleton, and segmented body. These distinct characteristics make them most stable biological creatures for multidirectional locomotion. To take the advantage from distinguish feature and abilities of arthropods engineers are continuously challenging there limits and capabilities [2]. With the help of modern technology and after years of research, it is possible to construct an artificial walking machines to emulate the walk of insects. Tripods, Tetrapods, Hexapods and Octopods structurally resembles arthropods which allow these walking machines an extra stability during their locomotion. Hexapods possess greater static and dynamic stability. Therefore we have implemented hexapod robot which has the ability to transform itself into a Bipod, Tripod or Tetrapod. When any of its legs malfunction, the robot will autonomously reconfigure itself while keeping the mechanical stability. Hexapod have many advantages over the wheel locomotives but it also possess the complexities in its design, orientation, gait pattern, manufacturing, assembling navigation and control. All the six legs must be in perfect coordination to

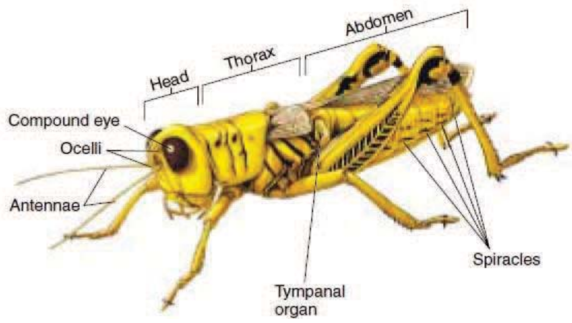

Fig 1 Structural features of Arthropods

produce versatile, effective and elegant movement. Each leg has three degrees of freedom (3 DOF) producing eighteen degrees of freedom (18 DOF) in total. The high number of DOFs make the coordination between the joints of hexapod a challenging task. The coordination between each joint of robot can be effectually done by adopting distributed electronic system [3].

Self-reconfiguration, self-optimization, and self-healing systems are highly desirable attributes of next generation robots. Such characteristics enable the robots to continue its task even in case of system failure. The self-X features will enable the robot to control and adapt itself in any terrestrial or extra-terrestrial environment without any human intervention [4].Hexapod implemented here is adaptive to its surroundings. Under normal conditions when all six legs are operational robot can change its walking sequence with or without human interference. This ability allows the robot to maintain steadiness during its locomotion in different terrains which enhances its functionality. Robot mention in this paper has multiple gait patterns and can switch the gait according to requirement.

The mathematical model based on kinematics and inverse kinematics enable us to predict the position, orientation and motion of robot allowing to mimic the natural locomotion of arthropods. Model based on mathematical equations also reduced the complexities present in the control and navigation of robot. The hexapod robot is implemented keeping in mind the reduced cost and complexities.

II. MECHANICAL STRUCTURE RESEMBLING ARTHROPOD'S BODY

Development of jointed and segmented body of arthropods is one of the most magnificent contribution during evolution. Jointed appendages has provided the functional flexibility to

978-1-4799-2060-0/14/$31.00 ©2014 IEEE

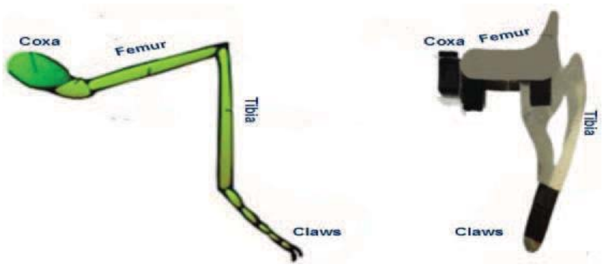

Fig 2 (On right side) Leg of Arthropods and imitated leg for hexapod (Left side)

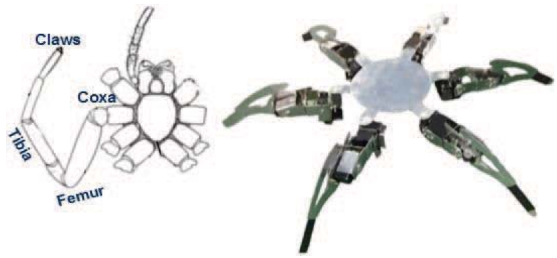

Fig 3 (Right side) Dorsal side of spider with proposed circular shape hexapod mechanical structure (Left side)

arthropods which has transmuted them into most successful group of living beings. They use their jointed appendages to perform different tasks. They use mouth parts for feeling, antennas for sensing their habitat and multiple legs for walking. Another most important feature of arthropods segmented body is there exoskeleton which provide them stability during their motion. Presence of jointed appendages, exoskeleton, and segmented body has allowed the arthropods to effect all the aspect of human life. Figure 1 shows the major structural features of arthropods. Multiple legs are present in arthropods that range from 4 to 8. It differs from kind to kind. Legs are connected to the thorax the centre part of body which is further divided in to three parts. Prothorax is first, middle part is mesothorax and last one is metathorax. Arthopod legs consist of coxa which is the part connected to thorax . Femur and Tibia are the other significant parts of leg.Thorax is articulated with the coxa section of the arthropods leg. It plays very important role of pushing the body forward during the locomotion. Femur is the most robust part of the leg which generates high stress. The largest segment of arthropods leg is Tibia which provide the necessary offset from the ground and allow the arthropods to change their height. By analogy, the completed structure for robot leg was assembled which resembles the arthropods leg as shown in the Figure 2. The modelled leg of this robot with its each analogical part imitates the same job as performed by the parts of the legs of real arthropods. Similar approach is mention in [5]. Central part of the hexapod is inspired by the mid sphere shaped body of the spider, to which it's all legs are joined as shown in Figure 3. Circular structure is the best figure to provide the necessary balance as its radial point is equidistant from every point on its circumference. Thereby, base frame of the hexapod is made circular and each of its six legs are connected to it in order to provide with the equal weight distribution of its body onto the legs. Any other shape, may it be triangular, rectangle or random trapezium is not used for the key frame of hexapod due to irregular shift in the centre of gravity while it will be in motion. To attain the static and dynamic stability during its kinesis circular shape is preferred, the centre of gravity in that case always lie at the origin and thus stability retains. Figure 3 demonstrates this idea of circular frame adopted for hexapod in comparison to nature's spider.

III. MATHEMATICAL MODEL

Before any implementation of the hardware electronic system, its test in virtual environment (simulation) is necessary. In the same fashion, for the physical existence of robotic structure, its mathematical modelling is of crucial importance. Mathematical modelling well presents the whole design summary of the robot dynamics in the form of parametric equations. It assists to choose more feasible, established and settled design. Theory of forward and inverse kinematics provided the way out to model the proposed hexapod. Similar characteristics robot are mention in [3], [4], [5], and [6].

A. Forward Kinematics

Forward Kinematics explain the connection of the individual joints of the robotic machines and in addition to that it also frames for the positioning and alignment of end-effector. Figure 4 is forward kinematics configuration for a leg.

With the given values of joint variables, coordinates can be extracted. Homogenous transformation matrix for a given leg of the hexapod can be determined by using the Denavit-Hartenberg (H-D) Convention [7], [6]. This representation is composed of four transformations.

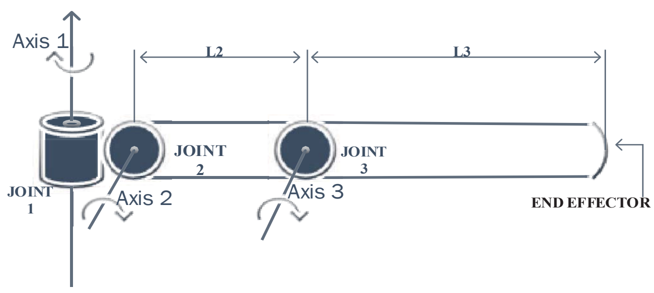

Fig4 Forward kinematics configuration for a leg

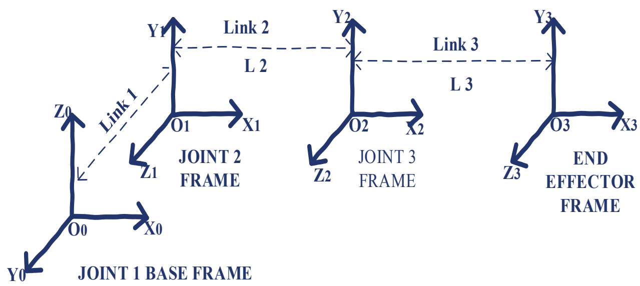

Fig 5 Frame assignment for robot leg

TABLE 1
LINK PARAMETERS

$\mathbf{Link}_i$	α_i	a_i	$\cos\alpha_i$	$\sin\alpha_i$	d_i	Variables
1	90	0	0	1	0	θ 1
2	0	L1	1	0	0	θ 2
3	0	L2	1	0	0	θ 3

$$H = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix} \quad (1)$$

- **R**=Rotational matrix
- **d**=Translational matrix
- **0**=Representative matrix
- **1**=Scalar matrix

Figure 5 shows frame assignment of three revolute joints for creating 3 RRR manipulator giving 3 DOF. Joints 1, 2, 3 are the analogy for coxa, femur and tibia respectively for the suggested hexapod. Axis 1, 2, 3 are the representative of $\theta_1, \theta_2, \theta_3$.Figure 5 displays the Frame assignment for a 3 DOF leg. The general form of H-D convention is mentioned as:

$$A_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & ai\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & ai\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

By using the link parameters given in Table 1, a general matrix for H-D convention can be reduced to individual matrices for the joints as given in (4),(5),(6). Product of the individual transformed matrices can be given by utilising:

$$T_3^0 = A_1^0 A_2^1 A_3^2 \quad (3)$$

Transformation metrics for each joint can be define as following by using (2).

$$A_1^0 = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ \sin\theta_1 & 0 & -\cos\theta_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$A_2^1 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & L_2\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

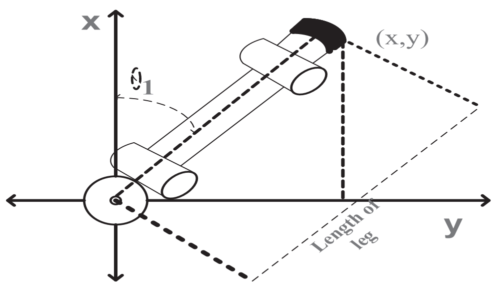

Fig 6 Model for inverse kinematics in x, y coordinates (Top view leg)

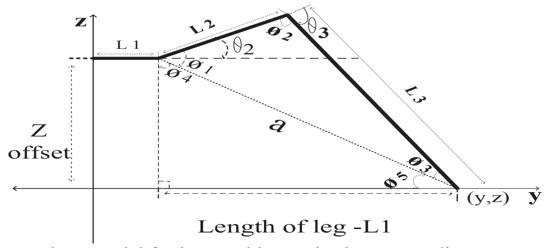

Fig 7 Model for inverse kinematics in z y coordinates (Side view of leg)

$$A_3^2 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & L_3\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & L_3\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Parametric equations are deduced by making use of (3).

$$\begin{aligned} x &= L_2\cos\theta_1\cos(\theta_2+\theta_3) + L_3\cos\theta_1\cos\theta_2 \\ y &= L_2\sin\theta_1\cos(\theta_2+\theta_3) + L_3\sin\theta_1\cos\theta_2 \\ z &= L_2\sin(\theta_2+\theta_3) + L_3\sin\theta_2 \end{aligned} \quad (7)$$

B. Inverse kinematics

Through inverse kinematics joint variables can be calculated using given coordinates of orientation. There are different methods to derive inverse kinematics equations. For the mentioned hexapod geometric method has been used. The first issue that needed attention was the representation of 3-D design on 2-D paper, this task is easily done by resolving one design into two figures. By using divided images all three joint variables can be calculated. Figure 6 provides the top view of leg motion in x, y coordinates in Figure 6. Z axis is out of the paper and towards the reader. θ_1 can obtain by inverse tangent function as shown in figure 6 this approach can be verify from [5],[6] and book reference [7].

$$\theta_1 = \tan^{-1}(y/x) \quad (8)$$

Length of leg is the hypotenuse of triangle in figure 6 given can be calculated by using Pythagorean Theorem.

$$\text{Length of leg} = \sqrt{x^2 + y^2} \quad (9)$$

Figure 7 represents the side view of a leg in y, z coordinates and θ_1 and θ_2, can be easily calculated using some basic

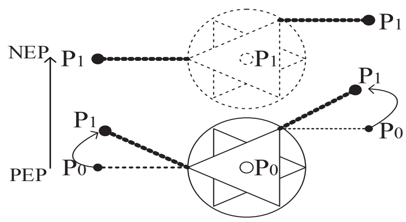

Fig 8 Bipod crawl---PEP is Previous Extreme Position at P0, NEP is Next Extreme Position at P1

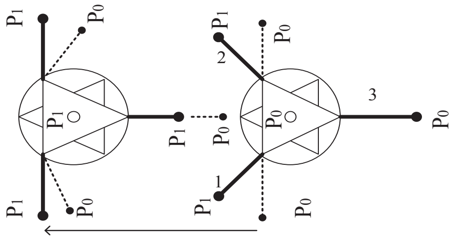

Fig 9 Tripod walk---PEP is Previous Extreme Position at P0, NEP is Next Extreme Position at P1

trigonometric identities. The resultant vector 'a' divide the total angle between the lines L3 and L1+Length of leg into two angle and its magnitude can be given by:

$$a = \sqrt{(\text{Length of leg} - \mathrm{L}_1)^2 + \mathrm{Z}^2} \quad (10)$$

$\emptyset_1$ is angle between L2 and resultant vector 'a' and $\emptyset_4$is present among perpendicular line on y axis and resultant vector 'a'. By calculating values of these two angle we can find out θ_2 as:

$$\theta_2 = \emptyset_1 + \emptyset_4 - \frac{\pi}{2} \quad (11)$$

Using law of cosines we ca write $\boldsymbol{\theta_2}$:

$$\theta_2 = \cos^{-1}(\frac{\mathrm{a}^2 + \mathrm{L}_2^2 - \mathrm{L}_3^2}{2\mathrm{aL}_2}) + \tan^{-1}(\frac{\text{Length of leg} - \mathrm{L1}}{\text{Z offset}}) - \frac{\pi}{2} \quad (12)$$

θ_3 can also be calculated from the figure 7

$$\theta_3 = \pi - \cos^{-1}\left(\frac{-a^2 + L_2^2 + L_3^2}{2L_3L_2}\right) \quad (13)$$

IV. MULTIPLE GAITS PATTERNS FOR ROBOT

Hexapod is made able to sneak in different walking sequence, which are:

A. *Bipod crawl*

Bipod indicates two legs. Bipods exhibit simple walking pattern but here bipod crawl refers to the creeping of hexapod with its any two legs. The crawl it makes with its two legs follow stance and swing phases. Both of its legs are in swing position together, making the advancement towards the position it has to attain and in stance it drags the body to that position, completing one gait cycle. Snippers crawl well defines bipod crawl. Figure 8 shows the pattern of bipod crawl.

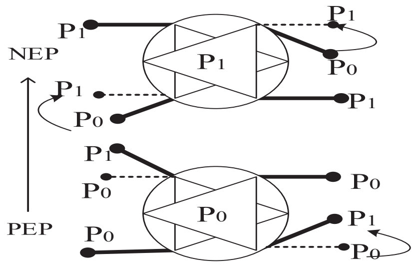

Fig 10 Tetrapod walk----PEP is Previous Extreme Position at P0, NEP is Next Extreme Position at P1

B. *Tripod walk*

Tripod gait is explained in a way that its leg1 reaches the position (P1) leaving its initial position (P0). The remaining two legs are in stance position that time. Now when the leg1 has moved, leg2 leaves position (P0) and reaches at position (P1). In third step while tripod is trying to move forward, leg3 comes in swing phase after pushing the body towards its destination. Finally hexapod has made its step forward in a tripod walk.

C. *Tetrapod walk*

Tetrapod walk pattern is given to the suggested hexapod by getting inspiration from the four legged mammal's gait. It is more stable way of walking. Weight is distributed on all four legs giving complete balance in dynamic as well as static states. Exact sequence that it would follow is showed in figure 10.

D. *Hexapod walk*

Hexapod has two main walking orders as:

In insect-wave tripod gait the three legs at the corners of isosceles triangle together are lifted up to go in swing phase, the other three legs are in stance phase at this instant. The body is pushed in the forward direction as the legs in the stance phase go to swing phase making one complete gait cycle.

In mammal-kick tripod gait of hexapod, one leg at the leading corner of isosceles triangle pull the body and the two legs at the lower corner of triangle push the body in same

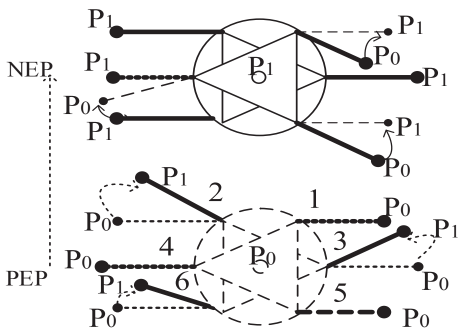

Fig 11 Hexapod insect wave walk ----PEP is Previous Extreme Position at P0, NEP is Next Extreme Position at P1

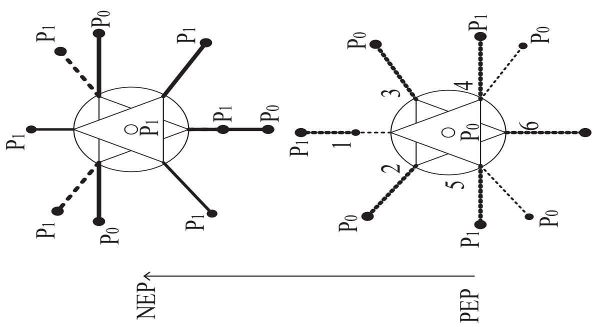

Fig 12 Hexapod mammal kick gait ----PEP is Previous Extreme Position at P0, NEP is Next Extreme Position at P1

TABLE 2
SUMMERY OF LEG SEQUENCE FOR ONE COMPLETE GAIT CYCLE

PHASE	BIPOD CRAWL	TRIPOD WALK	TETRAPOD WALK	HEXAPOD WALK
Swing	Any two legs	Leg 1	Leg 1,Leg 4	Leg2,Leg3 Leg6
Stance	Any two legs	Leg3, Leg2	Leg 2,Leg 3	Leg1,Leg4 Leg5
Swing	-----	Leg 2	Leg 2,Leg 3	Leg1,Leg4 Leg5
Stance	-----	Leg 1, Leg3	Leg 1,Leg 4	Leg2,Leg3 Leg6
Swing	-----	Leg3	-----	-----
Stance	-----	Leg 1,Leg3	-----	-----

orientation. As this is done, the remaining three legs at the vertices of second triangle come in action, one at front, push the body and the next two pull it to move ahead. This walking sequence is imitated from human gait, as could be seen in figure 12.

V. SELF-RECONFIGURATION AND GAIT SWITCHING

Proposed hexapod is made capable to reconfigure itself whenever it faces misbalance due to loss of its leg or when any of its leg malfunctions and do not give response. Hexapod robot observe the sequence of failure in its legs and adopts the best matched geometry (bipod, tripod, tetrapod) Reference [10] also discuss about the similar idea.

A. Single leg lost

When one leg of hexapod is broken or has stopped responding, it achieves tetrapod geometry by disabling one more leg itself. Figure 13 A) shows penta-leg configuration, the programmed hexapod sense this fault, inactivates another leg that is opposite to the faulty leg and balance itself on four legs to complete the task. Figure 13 B) is the final shape hexapod has adopted.

B. Two legs lost

If fortunately opposite two legs of the hexapod are broken, it will easily manage itself for tetrapod gait. If any two random legs are broken, still it achieves tetrapod formation by sometime rotating its frame or by tilting its legs but this tetrapod might be less stable and can face difficulty in its mobility. Reference [12] has also discuss similar idea.

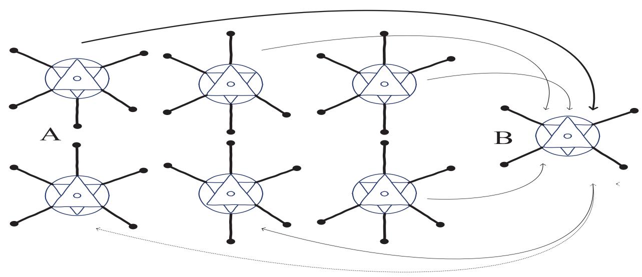

Fig13 Reconfiguration when one leg loss. A) shows loss of one leg B) shows hexapod after reconfiguartion

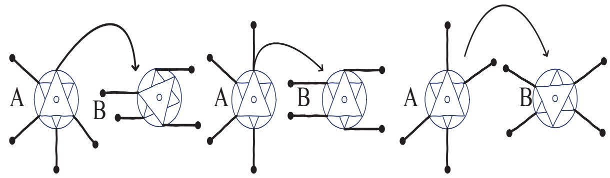

Fig 14 Reconfiguration when two legs loss. A) shows loss of one leg B)

C. Three legs left

Now the situation comes when three legs of the hexapod are damaged, this time it will redefine itself in either tripod or bipod construction. If alternate legs are destabilized then it achieves tripod geometry to keep going and if adjacent legs are malfunctioned, hexapod immobilizes the central leg of the three and adopts bipod formation. In bipod formation it starts creeping on the ground.

D. Survival on two legs

Hexapod is programmed in a way to even persist in worst case scenario when it has lost four of its legs. It succeeds to carry on its motion on the two remaining legs in the bipod shape. Self-reconfiguration is achieved by the hexapod during its motion i-e whenever failure of any leg is noticed, it stabilizes itself on the left over legs and continue to finish its assigned mission. This makes it more reliable and stable mechanical structure with good obstacle defeating capacity. Some related work can be found in reference [9] and [11].

Gait switching is defined by user as per requirement. It is done before assigning any task to the robot. It is independent of any flaw in its legs and can be achieved at any time when operator wants to switch its gait from one walking pattern to the other. This can prove to be power efficient and energy savior.

VI. DISTRIBUTED ELECTRONIC SYSTEM

The electronic system for this robot is distributed in three fragments as show in figure 20:

1. A hand-held device for wireless communication
2. Master controller embedded on the main frame of hexapod to receive signal from the communicating device
3. Slave controllers implanted on each coxa to communicate with the master controller.

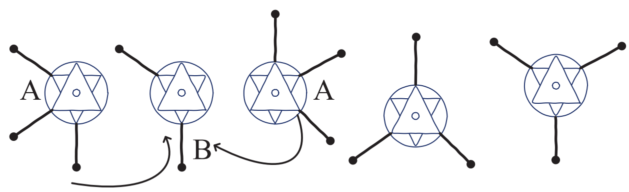

Fig 15 Reconfiguration when three leg lost. A) shows loss of three legs B) shows hexapod after reconfiguration

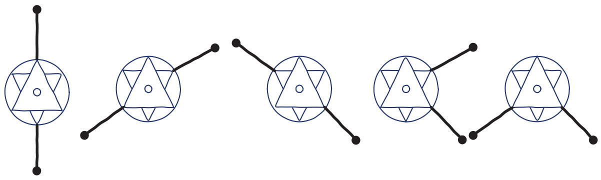

Fig 16 Reconfiguration when four leg lost.

The core mother controller mounted on the central body of the hexapod machine operates with the guidance of operator, it interfaces with the user and make its body execute the given task. The principal microcontroller further makes a link with six controllers present on the coxa part of each leg. Communication between the basic controller and six sub controllers is through SPI (Series Peripheral Interface) bus. Slave microcontrollers after the completion of assignment provides feedback to main controller. If this feedback is not provided by the slave controller in a fixed time instant, the master controller considers that leg to be malfunctioned. Master controller is the CPU of the hexapod, it includes all the functioning of gait switching, algorithm for reconfiguration and module to derive forward and inverse kinematics for the slave controllers. Slave controllers accomplish all the tasks as indicated by the head controller. Each slave controller generates a signal for three servo motors as shown in figure 18. Pre-programmed servo motors execute the received commands from the slave controllers. Claws of the hexapod have force sensors that keep controllers (on the coxa) well informed about which leg is in swing phase and when it goes to stance phase, by making and breaking contact with ground. Such system is also discuss in [3] and shown in figure 19.Block diagram for electronic system for hexapod leg is presented in figure 20. Each servo motor is being controlled by the servo control algorithm in salve microcontroller. Navigation of robot is mostly depends on the feedback of sensor [8]. Sensors play the most important task to navigate the robot.

VII. CONCLUSION

The execution of biologically inspired self-reconfigurable hexapod robot, exhibiting different walking patterns is explained in this paper. It is testified for self-reconfiguration

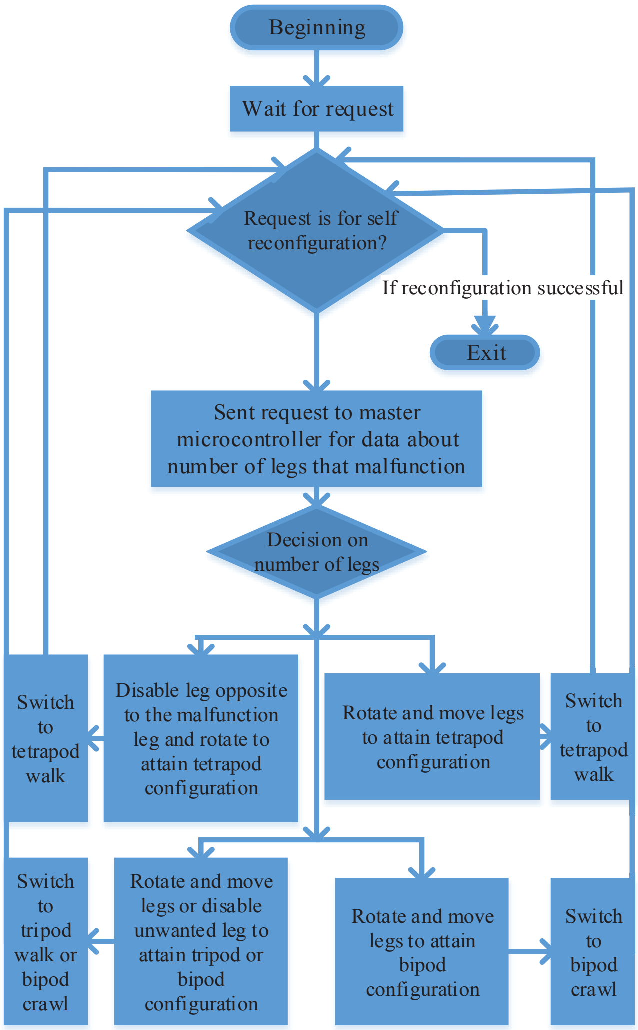

Fig 17 Flow Chat for self-reconfiguration

that is whenever it detects any fault in its limb or any malfunctioning is observed, it redefines its arrangement due to its gait switching ability. This makes it to adapt any habitat. Users can reprogram it according to the requirement for any function they want to execute. Each claw of the hexapod robot is provided with sensors that provide necessary data to

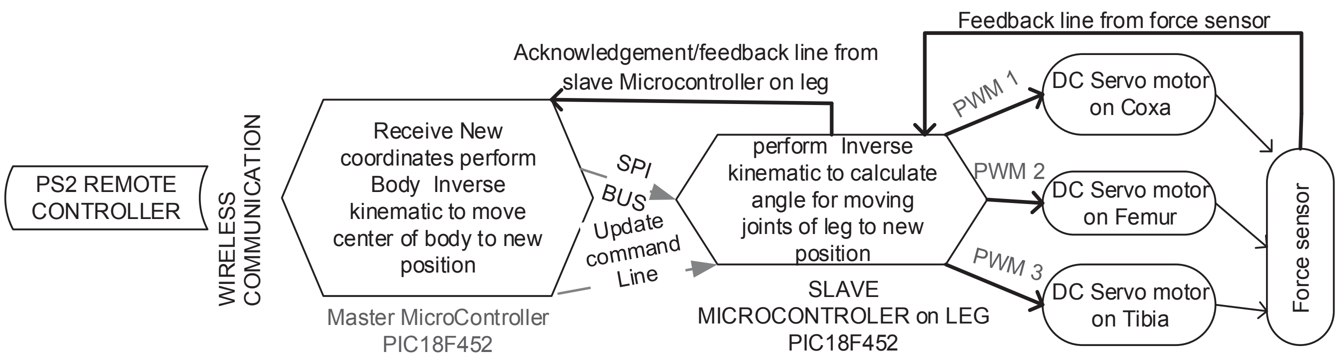

Fig 18 Layout of Electronic Control Architecture for single leg

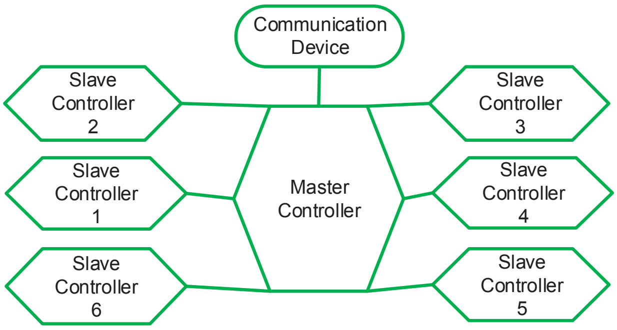

Fig 19 Complete Schematic of Distributed Electronic System

microcontroller for decision making. Proper algorithm is available within the master microcontroller to evaluate the particular situation for the execution of reconfiguration mechanism. Hexapod is implemented using mathematical derivation of forward and inverse kinematics theories. Each joint of hexapod is brought in motion with the help of servo motors. Motors provide 18 DOF that is overall controlled by the distributed electronic control system. Each leg of hexapod robot uses separate controller for the execution of its assignment. The electronic system is fully capable of sensing its surroundings and making decisions. This hexapod is efficient and its implementation is budget limited.

ACKNOWLEDGMENT

This work is completed with the support and appreciation of our parents and generous supervision and guidance of our respected teachers Dr Muhammad Adnan and Mr. Muhammad Ilyas Khan, both are assistant professors at department of Electrical Engineering, UMT.

REFERENCES

[1] J. M. Benyus, “Biomimicry: Innovation Inspired by Nature”, 1997.

[2] H. Cruse, “What mechanisms coordinate leg movement in walking arthropods,” *TINS,* vol. 13, pp. 15-21, 1 November 1999.

[3] D. Belter, K. Walas and A. Kasinski, “Distributed control system of DC servomotors for six legged walking robot,” in *Power Electronics and Motion Control Conference, 2008. EPE-PEMC 2008.*, 1-3 Sept. 2008.

[4] Brockmann.W, Maehle.E and Mösch.F, “Organic Fault-Tolerant Control Architecture for Robotic Applications,” in *4th IARP/IEEE-RAS/EURON Workshop on Dependable Robots in Human Environments*, Nagoya, Japan, 2005.

[5] O. Botello, M. García, P. del Carmen Zambrano Robledo and A. Velázquez, “Design of a Hexapod Robot Based on Insects,” in *Electronics, Robotics and Automotive Mechanics Conference* , (CERMA), 2010.

[6] J. Ollervides, J. Orrante-Sakanassi, V. Santibanez and A. Dzul, “Navigation Control System of Walking Hexapod Robot,” in *Electronics, Robotics and Automotive Mechanics Conference (CERMA), 2012 IEEE Ninth* , Nov.2012.

[7] M. W. Spong, S. Hutchinson and M.Vidyasagar, Robot Modeling and Control, John Wiley & Sons, 2005.

[8] R. Canham, J. R. and A. Tyrrell, “Robot Error Detection Using an Artificial Immune System,” in *Proceedings of the 2003 NASA/DoD Conference on Evolvable Hardware*, 2003.

[9] Ing, R and Woering, “Simulating the "first steps" of a walking hexapod robot,” January, 2011.

[10] D. Zhuo-hua, F. Ming, C. Zi-xing and Y. Jin-xia, “An adaptive particle filter for mobile robot fault diagnosis,,” in *Journal of Central South University of Technology,* 2006.

[11] J. Bojan and M. Erik, “In situ self-reconfiguration of hexapod robot OSCAR using biologically inspired approaches,” InTech, 2010.

[12] Xilun Ding, Z. Wang, A. Rovetta and J. Zhu, “Locomotion analysis of hexapod robot,” InTech, 2010.

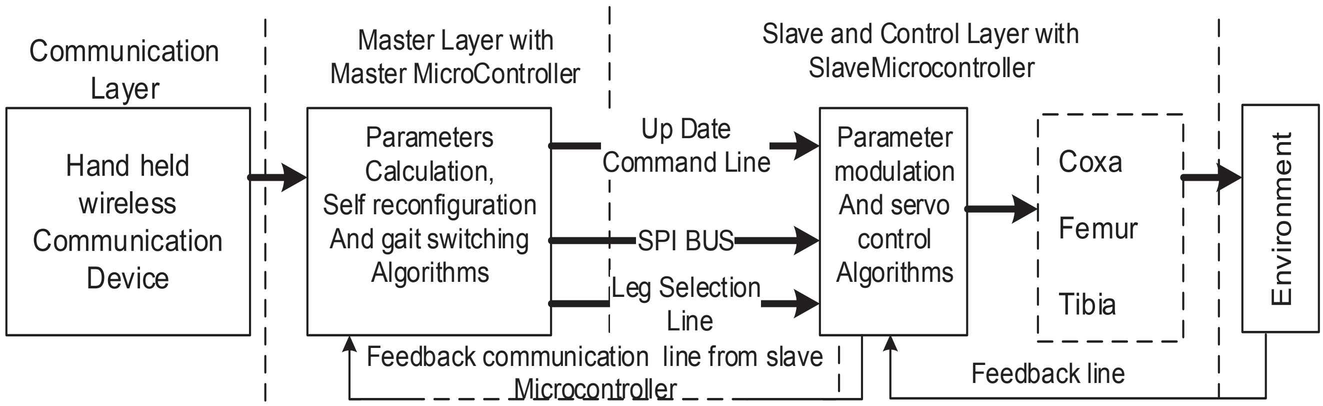

Fig 20 Fragments of Distributed Electronic System