Design and testing of Central Pattern Generator gait testing platform for Hexapod with reflex learning

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ABSTRACT

Background: This paper models a six-legged robot (hexapod) built using 18 servo motors which gives 3-degree of freedom for each leg. This model is used to demonstrate the dynamics of common 6 legged insects in the nature. Objective: The main aim of this paper is to analyze the unsupervised learning mechanism of hexapod locomotion. The electronics used in the robot body is just to provide independent control signals for servo motors and to establish a wireless communication between the robot and a laptop. The wireless communication used is Bluetooth, which establishes a communication with on-board Arduino UNO board and the java locomotion algorithm application in the remote PC. Results: The results of the analysis show that The Application base establishes a link to send the pulse width modulation (PWM) duty cycle settings to the Arduino and receives sensory feedback signals from it. Arduino board sets the duty cycle of 18 pwm channels controlled using two PCA9685 PWM controllers. With the available data from the robot algorithm synthesizer sets an algorithm for the robot and with the feedback signals it learns to update the locomotion algorithm and improves the speed of walking with the terrain.

KEYWORDS: Hexapod, Central Pattern Generator, Artificial Neural Network, Unsupervised Learning.

INTRODUCTION

Legged robots have extremely useful applications in uneven terrains e.g. accomplishing rescuing and detecting tasks in the earthquake and nuclear accidents instead of human beings. In such environments wings and wheels won’t have any satisfactory performance. With a smaller size and legged structure we can make the detector to perform better than any other structure. But the problem with an autonomous legged robot lies in finding their path in the uneven terrain, and adjusting its parts for the unpredictable situations of the environment. Human controlled robots will introduce the problem of visual, and distance limitation. In an earthquake situation the visual will not be available for the remote user to control the robot. Even with a camera user needs much time to understand the surrounding terrain of the robot, in low light the situation becomes much more severe.

There are several studies were taken place in the topic of autonomous terrain adaption for legged robots. The Big Dog from Boston Dynamics is a four legged robot that can pass irregular terrain using the trot gait based on balance algorithm [1]. RHex [2], [3] is a compliant-legged hexapod robot which can travel rough terrains without complex control algorithms. The compliant legs can reduce the impact of external force on RHex and provide it with impressive terrain adaptability. Yasuhiro Fukuoka, Hiroshi Kimura and Avis H.
Cohen [4] used a PD controller at each of the joints in the quadruped robot. The PD controller is used to model the virtual spring-damper system as the visco-elasticity model of a muscle, that plays an important role in the body stabilization and system energy storage. Apart from the bionics design in the mechanism, some researchers have also developed a novel control algorithm the central pattern generator (CPG) [5] inspired by the principal of the biological control scheme. The quadruped robot Taken [6] can walk with a medium walking speed on the irregular terrain based on the neural system model consisting of a CPG and reflexes.

2. Literature review:

Most of the related studies satisfy the requirement of adaption to complex terrains by using the balance control algorithms and the special design concept of legs. In recent years, due to the vast developments of vision sensors and force sensors, control methods combined with these sensors have been developed, which provide legged robots with the sensing ability. After having a good knowledge of the site environment, legged robots can select a safe path and a set of appropriate footholds initially, then plan the feet and body motions effectively in order to traverse rough terrains with high stability, velocity and low energy consumption.

The use of sensors especially vision sensors and force sensors plays an important role in the robotics field, and is a higher level application of the biological engineering. There has been some work concerning the motion planning for legged robots based on vision sensors. The Little Dog [7], uses the laser scanning system and the external motion capture system to model a high resolution terrain map around the robot, then the terrain map is processed in quantity. The control strategy of LittleDog includes three parts, a system that learns optimal footholds choices, a body trajectory optimizer and a floating-base inverse dynamics controller, which allows the LittleDog to perform a fast locomotion over the rough terrain. Stephane Bazeille et al. proposed a control scheme for the quadruped robot HyQ, which performed the goal-oriented navigation on the unknown rough terrain by using the inertial measurement data and the stereo vision. The six-legged walking robot DLR [10], [11], [12] can navigate in rough terrains. The control system of DLR uses the SGM method to build the digital elevation map, then defines the traversal index and plans the path concerning about the information of legs dimension sizes, the body posture and the obstacles distances.

3. Problem Definition:

This paper suggests a new operating structure for the six legged robot locomotion. The controlling signal for the robot is generated from the understandings of the dynamic terrain conditions. This avoids the need of the remote user to control each and every part of the robot and reduces the data transfer in the wireless channel. For the purpose of demonstration the unsupervised learning mechanism for the robot locomotion algorithm is implemented in the remote computer to make use of a powerful computer. The central pattern generator (CPG) is the part which generates the rhythmic oscillations required for the locomotion in almost all vertebrates. This CPG is implemented in the remote PC in software which sends the control signal for each joint in the robot. Each leg has a force sensor to feedback the part of bodyweight that share with all other legs. The gyroscope in the body is aligned with the default stable balanced position of the robot, thus feedbacks the tilt of its body to the control system. An ultrasonic sensor with the capability of 2 degree of freedom makes it to observe objects in the path and to analyze its height to a limited extent. The robot has preprogrammed basic gait patterns, and from which it improves the gait for the terrain. This preprogrammed gait evolved from the general gait patterns observed in the nature.

4. Model Formulations and Assumptions:

A. Prototype:

![Robot Arm Assembly](image)

Fig. 1: Robot Arm Assembly
The hexapod robot is a six legged robot with 3 degree of freedom in each leg. It is the platform for the integrated walking and manipulating. The main application of this robot lies in the harsh environments where other wheeled robots cannot perform satisfactorily. There are several six legged insects in nature but this paper used a hexapod structure which is much more similar to the tiger beetles which is the fastest six legged insect. The body of the robot is not exactly square but a rectangle with increased length to one direction which gives a perfect identifiable front, back, left and right side of the robot. Therefore the legs are said to be distributed in left and right side of the robot. All the legs have the same dimensions and are symmetrically arranged to the robot body. Every leg has three joints connecting three parts of the leg named Coxa, Femur and Tibia. Each joint is a revolute joint and controlled using a servomotor. The servomotor is able to provide an angle of rotation at its shaft of total 180 degree. The angle depends on the duty cycle of the pulse width modulation (PWM) signal at the input. Each joint need not to have the full 180 degree operation but varies with the gait. Coxa is the part that connects the leg with the hexapod body with a revolute joint. Then the Coxa connects to the Femur through another revolute joint but its freedom plane is orthogonal to the Coxa revolute joint. The third revolute joint connects the Femur part and the Tibia which is the end effector for a leg and interacts with the ground and it also lies in the same plane of the previous joint. This arrangement of the leg parts allows it to rotate and achieve a position anywhere in a spherical space of a diameter equal to the total effective length of the leg, but actually hexapod legs need very limited orientations in the space. The sophisticated terrain adaptation is possible with the joined orientation of the different legs as seen in the animals where they usually adapts their body to maintain the center of gravity within a limited area. Each leg’s Tibia has a switch to check whether it supports the robot weight at times. This makes the robot to have different leg combinations in passing through an uneven terrain by checking the balance of the total robot. Gyroscope provides the information about the stability of hexapod. An ultrasonic sensor connected with two servomotors provides the capability of detecting objects in the path and also its height.

![Fig. 2: Complete robot assembly](image)

Hexapod will be applied in environments where humans direct interactions will be restricted. Therefore a sufficient intelligence will be developed for it to take decisions within the environment and reduce the data transmission. However in this paper the intelligence is developed in a remote PC where the electronics in the robot is just used to take commands from the PC and to send different data collected from the environment to make command. This mode of operation is followed just avoid to reduce the expense of installing high performance computer system in the robot which introduce problems like need of high electric power, increased size, weight and need of high torque servo motors. Since this is just an experiment of the algorithm this is not a problem and also gives the capability of trying different algorithms in high level language.

The mode of operation of the hexapod for this particular application is seen as in the block diagram. The Arduino interacts with the I2C PWM controller to set the position of all servo motors. Arduino is also connected to various sensors in the robot body. All these data are accessible from a remote PC through a Bluetooth link connected to the serial port of the Arduino. The I2C PWM controller used is a chip PCA9685 from NXP semiconductors. It is an independent 16 channel PWM duty cycle controller which can operate in 40Hz to 1600Hz PWM frequency and duty cycle can be set with a 10bit width register available for each channel. The servomotors used in this paper operate in a PWM frequency of 50Hz-60Hz and therefore PCA9685 is very suitable for this application. PC receives and sends the data through a Bluetooth link from/to the hexapod. An application created in Java communicates with the robot. It also models the robot dynamically in software and uses the data received from the robot to make decisions for the gait pattern for the different terrains. Neuroph
library available in java language provide the basic neural networks and is used to model the Central Pattern Generator of the robot. The robot model in software continuously trains the CPG from the feedback.

5. PWM Controller and Servo Motor:

The PWM controller PCA9685 has totally 16 channels and two of them needed to connect 18 servos in the system. They have an I2C interface to communicate with the arduino. In the real-time usage we can replace arduino with a small computer board like Raspberry Pi and it also provides an I2C interface. I2C communication is a two wire communication, a clock line and data line. It has a speed of 100kbps to 400kbps which is more than enough to control all the servos. The servo used in this application is SG90 servo from Tower Pro which is an analog servo. It operates in a range of 0-180 degree and the position is controlled with a PWM with on time from 1ms to 2ms range, i.e. 1ms is the extreme left and 2ms is the extreme right. Thus to set an angle at a joint we just need to send the corresponding 10 bit value from the Arduino to the PWM controller through the I2C interface. In this operation Arduino is the master and the two PWM controller acts as the slaves in the I2C bus. The two PWM controller is connected as right controller (RC) and left controller (LC) each drives the leg joints of corresponding sides. So in each PWM controller we have used only 9 channels. Use of this I2C interface reduces the burden of the Arduino in generating the PWM signal continuously. PWM controller also reduces the power consumption of Arduino and provides a better supply source stabilization for the servo supply. The servo motor draws a current from 20mA to 200mA. So while walking each joints takes a current in between 100-200mA. Also the varying duty cycle of the PWM signals in each channel also creates surges in the source supply of the PWM controller. To avoid the brown out condition of the Arduino due to this surge in the supply a large electrolytic capacitor in each PWM controller which compensates the surges.

C. Sensors and Bluetooth:

There are different sensors in an actual animal body that supports its locomotion in uneven terrains, and it’s very difficult to implement all those sensors in a robot body, but there are some essential senses one need to get for a successful locomotion. Robot body must be in a stable orientation throughout all transformation while it’s moving. This orientation may vary widely with the gait pattern. For an example usually we have four types of leg combinations in the hexapod locomotion. In each of them the stable orientation of the hexapod body varies widely with the shape of the supported leg geometry. A hexapod that keeps five legs in support of the body for whole time can have a large tilt to the body. So it situations at which a hexapod needs to travels through very ruff surfaces to overcome closer ups and downs can follow a five legged gait. Upon even surface we just need 3 legged gait which will give much more speed for the hexapod. On all these situations we need the relevant sensors to check the orientation and here used a gyroscope. The unsupervised learning algorithm checks the orientation of the hexapod and trains the neural model to keep use the same orientation in those instances. The switch sensor connected at each tibia of the robot make use to find which legs are at support at each instance. Another important sensor used is the ultrasonic sensor that used to find the objects that blocks the hexapod’s path. It is not efficient as any 3D image processing technique, but works similar to a radar. The two servos connected have the capability to move the ultrasonic sensor in XY plane and YZ plane. Therefore the signals from the sensor can be used to find out the height of the objects in the path and also their distance from the robot. Thus the robot can plan its path dynamically. These data also used to train the neural model of the robot.

Bluetooth interface used for the hexapod robot is an HC05 breakout module, which can be easily interfaced with Arduino serially. The two pin communication between the Arduino and HC05 uses AT commands, where we can use specific AT commands to manipulate the behavior of HC05 module.

D. Application Interface:

The neural network is modeled and experimented from a laptop computer which has a Bluetooth module. This helps us to have a powerful hardware to device, analyze and update the hexapod locomotion algorithm. The java language used to model the neural network model for the Central Pattern Generator for our hexapod. Then the oscillatory output signal is transformed into a 10 bit duty cycle for the PWM signal settings in the PWM controller for each channel. So for all the time the PC communicates to the hexapod through Bluetooth to control the joints. The only things the Arduino need to do is read the duty cycle setting from Bluetooth for each channel and update the PWM controller instantaneously. Arduino is also able to send the different sensor data to the PC. This signal makes the PC to device the CPG. Once in the Learning process the feedback signals from the tibia pressure switch is used to device leg combinations and the walking will be slow but if the trained data satisfactorily stabilizes the robot it fixes the gait for that particular terrain. The hexapod identifies the terrain from all its data from all sensors. Ultrasonic sensors greatly contribute in identifying the terrain.

E. Java Bluetooth Library:

Bluetooth is simply a wireless communication protocol. Since it’s a protocol we can use it to communicate with other Bluetooth enabled devices. Here we have the Bluetooth module in the Hexapod as a Bluetooth client
which establishes the connection with the remote PC to receive the data to make its movements and also to send data from its sensory feedback networks. Bluetooth is a great communication protocol because it can communicate at a speed of 1MBps and using very less power from the source. The Bluetooth stack is the software or firmware component that has direct access to the Bluetooth device. It has control over things such as device settings, communication parameters, and power levels for the Bluetooth device. The stack itself consists of layers, and each layer of the stack has a specific task in the overall functionality of the Bluetooth device. A Bluetooth Serial Port Profile is used to communicate between the client and server because this makes the communication easier to handle.

Fig. 3: Bluetooth Software model

F. Java Neural Network Library:

Neuroph is one neural network library that is well developed and documented as well as it is open source. Neuroph library implements the basic neural network architecture and supervised and unsupervised algorithms. This library is used to develop the neural network model for the Central Pattern Generator of the hexapod. The neural network model is selected from in a feed forward architecture and trained with specific training data set, which is said as the preprogrammed gaits. This training set models the hexapod’s CPG to have a basic gait pattern. With reflex signals or feedback signals the gait adapts to pass the uneven terrains. This data set from feedback for uneven terrain is concurrently used to train another CPG network and tries to implement in situations. So the hexapod has choices of CPG network for different terrains. A well trained CPG outputs a better gait for the hexapod. The switching of gaits is achieved by observing the feedback signals.

Fig. 4: Java Neuroph Library structure

G. Inverse Kinematics of Hexapod:

Inverse Kinematics model of the Hexapod is essential to deduct the required angle for each joint in the robot. The IK model uses the coordinate system of each link to calculate the overall transformed angle from moving the end effector from one point to another point. In the hexapod the IK involves in calculating the new angles for each servo motor while moving the leg from one point to another point. This calculation mainly involves at times when the CPG cannot continue the locomotion and the legs moves with the reflex signals. In unsupervised learning procedure this calculation need to do fewer times, since we uses the set of calculated
angles to train the CPG for the particular terrain. This reduces the need of recalculation after getting a sufficient training data for the CPG.

H. Central Pattern Generator:

Central Pattern Generator is the soul of the locomotion gait in the hexapod. We will have some preprogrammed gait patterns or CPG network in the hexapod. This will be a neural network of feed forward architecture and trained from a static data. These gait helps the hexapod to start their locomotion in all terrains. But then the feedback signal data set helps the hexapod to analyze its locomotion patterns. In situations where they troubled or decreased the performance. These makes it capable of reinventing gaits in similar terrains by implementing the CPG with parameters for that specific terrain training set. Thus there are several sets of training data grouped with difference in terrains. Once the hexapod identifies the terrain then it loads the CPG with the parameters that converged from training the CPG with the training data specifically for that terrain. I have used the neural network architecture that is proposed by the Cesar Ferreira in their paper “Quadruped Locomotion based on Central Pattern Generators and Reflexes”.

This architecture also proposes a feed forward CPG network that acts as a predictor of motor neuron signal from the limbs movement. But this paper proposes multiple set of parameters for different terrains that is trained with the data that acquired from the earlier locomotion through the similar surfaces. Thus the hexapod can have different gait patterns stored in them and the CPG network just get modified to produce that motor neuron activation when they identify that particular terrain.

6. Experimental Results:

The hexapod robot is built in a configuration as stated above and experimented with two preprogrammed gaits. The Tripod gait of hexapod is the usual gait pattern seen in 6 legged animals. In this gait three legs will be always supporting the hexapod body and the center of mass can be easily identified in the middle of the triangle that supports. This always ensures a maximum static stability and faster locomotion. But if we are using 4 legs to support the hexapod body as seen in the quadruped animals and in some hexapod the static stability increases but speed decreases. Since the training data set needed to train the CPG neural network must be big for a satisfactory model it was difficult to train the first two preprogrammed gaits. To update the CPG from the reflex data also needed large set of reflex, i.e the hexapod must have a long walk through each terrain. The difficulty was in identifying the terrain. The ultrasonic sensor does not perform well because it does not carry much information about the smaller irregularities of the terrain. A 3D visualization camera will help much to identify the terrain than the ultrasonic sensor. Network must be big for a satisfactory model it was difficult to train the first two preprogrammed gaits. To update the CPG from the reflex data also needed large set of reflex, i.e the hexapod must have a long walk through each terrain. The difficulty was in identifying the terrain. The ultrasonic sensor does not perform well because it does not carry much information about the smaller irregularities of the terrain. A 3D visualization camera will help much to identify the terrain than the ultrasonic sensor.

Fig. 5: Experiment output. A-D Shows the locomotion in a terrain where left and right side have different terrain structure. E shows the locomotion in normal terrain. F-H shows the locomotion in a uniform step terrain for both sets of leg.

There are mainly two models for hexapod in existence rectangular and hexagonal. Chu, KK and Pang, GKH made a comparison of the performance of hexapods in these two different models in their paper “Comparison between different model of hexapod robot in fault-tolerant gait [17]. In that paper they formed the conclusion that hexagonal design gives a better turning ability, stride length and stability margin in certain conditions. This paper uses the rectangular design for the hexagonal design. For an exact comparison result we need to design a hexagonal hexapod implementing the same gait algorithm. But from the comparison data for the hexagonal
hexapod in [17] we can say that this gait algorithm gives a better forward and backward locomotion in this rectangular model. The table below shows a comparison between the various parameters of the hexapod locomotion from the paper [18]. I have only taken the parameters from the same paper for the analysis. The previous values from the paper are mentioned in parenthesis for the understanding. The method had chosen for the calculation of parameters experiments taken similar to the author of [18]. If the gait stability was poor for a given test then gait variety could not be measured.

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<tr>
<th>Controller</th>
<th>Gait stability</th>
<th>Gait variety</th>
<th>Gait efficiency</th>
</tr>
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<tbody>
<tr>
<td>Reflexive</td>
<td>Good (Fair)</td>
<td>Good (Good)</td>
<td>Good (Fair)</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Good (Good)</td>
<td>Fair (Fair)</td>
<td>Good (fair)</td>
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<tr>
<td>CPG</td>
<td>Very Good</td>
<td>Very Good</td>
<td>Very good</td>
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7. Conclusions and Future Research:

The purpose of the paper was to implement the unsupervised learning mechanism for the CPG and reflex system of hexapod robot. The unsupervised learning system implemented in the high level language helps better to implement the neural network. The sensor network data is more important in the unsupervised learning. Since the servo motor used here have internal PID controller the duty cycle angle previously set is read as the feedback data, even then it gives a satisfactory unsupervised learning of the gait patterns. The problem identified was with the identification of terrain with the ultrasonic sensors. But using a 3D visualization camera may give good result in identifying smaller ups and downs. Since the different set of CPG parameters for different terrains the calculations involved for the inverse kinematics of the leg movement is reduced. Once got the satisfactory parameters for the CPG neural network for a terrain then we don’t need to depend on the reflex data, and thus the inverse kinematics calculations are also reduced for the total robotic system.

REFERENCES