Adaptive Control of Leg Coordination in a Hexapod Robot Using a Biologically Inspired Heterogeneous Neural Network

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Abstract:

Natural selection is responsible for the creation of robust and adaptive control systems. Nature's control systems are created only from primitive building blocks. Using insect nerurophysiology as a guide, a neural architecture for leg coordination in a hexapod robot has been developed. Reflex chains and sensory feedback mechanisms from various insects and crustacea from the basis of a pattern generator for intra-leg coordination. The pattern generator contains neural oscillators which learn from sensory feedback to produce stepping patterns. Using sensory feedback as the source of learning information allows the pattern generator to adapt to changes in the leg dynamics due to internal or external causes. A coupling between six of the single leg pattern generators is used to produce the inter-leg coordination necessary to establish stable gaits.

I. Introduction:

Traditionally robot control has been accomplished using a central computer which interprets all of the available sensory information, makes decisions based upon programmed rules and then controls the action to be taken. Such systems rely heavily on the ability of the designer and/or programmer to determine appropriate responses to a subset of all possible sensory input. An alternative to this type of design is behavior based or distributed control and has origins in biology.[1] Behavior based control is typified by the subsumption architecture, proposed by Brooks, which implements stimulus response pairs in a layered fashion to create desired behaviors.[2]

Entomological and biological data suggests that motor control in many insects and vertebrates is not solely a function sensory induced reflexes. Rather, motor control is most often performed by a central pattern generator augmented by sensory information.[3,4,5] However, in many cases the central pattern generator or the sensory reflexes are able to completely control behaviors even in the absence of the other.[6] The artificial insect project of Beer et al. demonstrated a neural network architecture for the control of hexapod locomotion based on the interaction between a central pattern generator and sensory information.[7,8]

The robot's we are interested in, as well as insects, live in a complex and changing environment. Not only is the external environment variable but the dynamics of the robots actuators may also change. A biological analog to this situation can be seen in the physical growth of limbs and strengthening or atrophy of muscles. In the biological situation, such changes are *sub-consciously* compensated for with little effect on coordination during routine use. The thrust of this research is to include this type of low level adaptability into robotics. Several implications of including low level adaptability are discussed at the conclusion of this paper.

II. The Robot Model:

The physical model that has been used for the hexapod robot is shown in figure 1. Each leg has two degrees of freedom at the joint between the leg and the body. Both horizontal and vertical leg positions, i.e. the angles θ and ϕ are measured with respect to references which are perpendicular to the body. The horizontal angle is defined as positive for positions anterior to the reference. The vertical angle is defined as positive for positions dorsal to the reference.

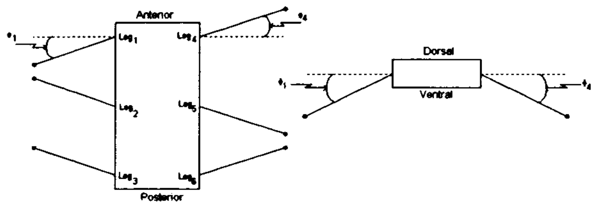

Figure 1 - Physical model of the hexapod robot. Both horizontal and vertical leg positions are measured from references which are perpendicular to the body. Horizontal angles are positive when anterior to the reference, vertical angles are positive when dorsal to the references.

The motion of each leg can be broken into four phases, two controlling horizontal motion and two controlling vertical motion. Horizontal motion of the leg, i.e. changes in the angle θ, consists of the retraction and protraction phases. The retraction phase is the movement of the leg from the anterior extreme position (AEP) to the posterior extreme position (PEP). During the retraction phase the leg is in contact with the ground and serves to propel the robot forward. During a protraction phase the leg is off the ground and swings from the PEP to the AEP. Vertical motion of the leg, i.e. changes in the angle ϕ, consists of the elevation phase and the depression phase. The elevation phase is a raising of the leg and the depression phase is a lowering of the leg.

Each leg is assumed to have two dc servo motors with associated feedback position control systems. The dc servos move the leg in the horizontal and vertical directions and are modeled using a second order transfer function. Two leg position control systems, one with ideal and one with non-ideal dynamics are used to illustrate the adaptability of the neural pattern generator (see section III. D.).

<u>III. Horizontal Leg Motion Pattern Generator:</u>

A. The Pattern Generator:

The pattern generator which controls the horizontal motion of each leg is modeled as a reciprocal inhibition network and is shown in figure 2.[9] A simple unipolar binary neuron model is used with threshold equal to zero and unity output when firing. The neuron outputs are passed through simple unity gain one pole RC high-pass filters to produce a time dependent decay. Each RC filter is assumed to have a voltage controlled reset switch which rapidly discharges the capacitor.

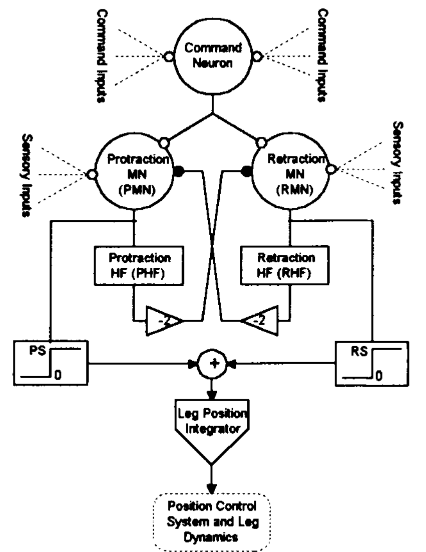

Figure 2 - The pattern generator for the control of horizontal motion in the single leg. Open circles at neuron inputs represent bi-directional synapses which can be excitatory or inhibitory. Filled circles represent rectifying synapses that only pass inhibitory inputs. RS and PS are system parameters and are measures of the retraction and protraction speed of the leg.

When the command neuron in figure 2 is firing (i.e. the robot has been commanded to walk) the reciprocal inhibition network will produce alternating retraction and protraction phases of horizontal motion. In the absence of any sensory inputs to the RMN and PMN the duration of each phase is determined by the time constants of the high-pass filters. For example the RMN will fire until the output of the RHF decays to half its maximal output thereby allowing the PMN to fire and inhibit the RMN. The duration of either of the phases can also be prolonged or shortened by the sensory influences. The reset switch of each high-pass filter is connected to the logical complement of the output of its associated neuron.

B. Sensory Influences:

The sensory inputs to the RMN and PMN of the pattern generator are based primarily on sensory influences and reflexes found in cockroaches and stick insects.[10,11,12] In biological creatures the sensory organs of interest are often found in antagonistic pairs. In the horizontal motion pattern generator an antagonistic pair of extreme position sensors is used. Each leg of the robot is equipped with a posterior extreme position sensor (PEPS) and an anterior extreme position sensor (AEPS). The response of the extreme position sensors to varying horizontal leg angles is shown in figure 3.

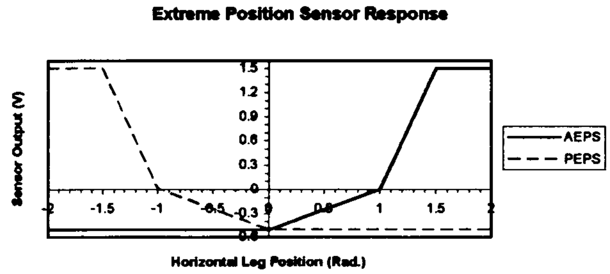

Figure 3 - Output of the extreme position sensors for the robot leg. The threshold of the sensors are +1 radian for the Anterior Extreme Position Sensor (AEPS) and -1 radian for the Posterior Extreme Position Sensor (PEPS).

The PEPS has a bi-directional synapse on the PMN and a rectifying synapse on the RMN. Conversely, the AEPS has rectifying synapse on the PMN and a bi-directional synapse on the RMN. The two extreme position sensors with these synapses combine with the reciprocal inhibition network to produce a chain of reflexes. When the leg exceeds the anterior extreme position (AEP) the AEPS excites the RMN, inhibits the PMN and a retraction phase is initiated. At the end of the retraction phase, if the leg exceeds the posterior extreme position (PEP), the PEPS excites the PMN, inhibits the RMN and thus initiates a protraction phase. Notice that the PEPS and AEPS only have an effect when the time constants of the high-pass filters are longer or shorter than the actual times required for the leg to retract and protract respectively.

C. Adaptation Mechanisms:

Adaptation is achieved in the pattern generator by modifying of the time constants of the high-pass filters. The nominal range of motion (i.e. the PEP and AEP) for a leg is set by selection of the thresholds of the PEPS and AEPS. The goal of the adaptation mechanism is to ensure that the retraction-protraction transition occurs at the PEP and the protraction-retraction transition occurs at the AEP. It is important to note that due to the dynamics of the servo motors and their controllers the actual position of the leg is unlikely to match the output of the leg position integrator of figure 2. Therefore, the adaptation of the pattern generator must be based on sensory information.

To facilitate adaptation based on sensory information a slope neuron is used. The slope neuron fires when the leg is protracting and is silent during the retraction phase. The output of the slope neuron is passed through a high-pass filter with a small time constant so that it decays quickly. Thus, the output of the high-pass filter pulses positive at the beginning of a protraction and pulses negative at the beginning of a retraction. The slope neuron circuit is shown in figure 4. The output of the slope neuron high-pass filter (SHF) in relation to the horizontal motion of the leg can be seen in figure 5.

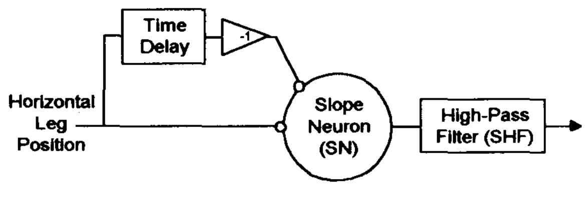

Figure 4 - Slope neuron circuit. The output of the high-pass filter will pulse positive at the beginning of a protraction phase and will pulse negative at the beginning of a retraction phase.

Changes to the retraction and protraction high-pass filter time constants are made when the motion of the leg changes phases. The RHF time constant is changed at the beginning of a protraction phase and the PHF time constant is changed at the beginning of a retraction phase. As described above the phase transitions of the leg are signaled by polarized pulses from the SHF. Hence, a positive (negative) pulse from the SHF triggers the learning mechanism for the RHF (PHF).

The time constant of the RHF is adjusted based upon the output of the PEPS at the time the RHF learning mechanism is invoked. If the output of the PEPS is greater than 0 V, indicating that the leg retracted beyond the PEP, the time constant of the RHF will be decreased. If the output of the PEPS is less than 0 V, indicating that the leg did not reach the PEP, the time constant of the RHF will be increased. This adaptation scheme causes the time constant of the RHF to converge to the actual time required for the leg to retract. The adaptation mechanism for the PHF is similar except changes in the time constant are based on the AEPS.

The magnitude of changes to the time constants is governed by a momentum learning rule.[13] The momentum rule significantly reduces the time required for the time constants to converge. Another advantage of the momentum rule is that after the time constants have converged the learning rate continually decreases. This prevents isolated disturbances from significantly affecting the time constants after they have converged.

D. Simulation Results:

Simulations of the horizontal pattern generator described above have shown that the adaptation mechanism enables the pattern generator to produce coordinated leg movements for varying leg dynamics. For the purpose of illustration several simulations are presented assuming an ideal controller for the leg servos (i.e. the actual leg position matches the leg position integrator output exactly.) Then the ability of the pattern generator to adapt to the leg/controller dynamics are demonstrated. These simulation are performed with RS=2.5 rad/sec, PS=5.0 rad/sec, PEP=-1.0 rad, and AEP=1.0 rad.

1. Ideal Leg Controller:

Figure 5 shows the output of the horizontal leg position integrator and the slope neuron. The value of the RHF time constant is initially too small causing retractions to end before the leg reaches the PEP. The value of the PHF time constant is initially too large causing protractions to continue even after the leg exceeds the AEP. Spikes in the SHF output indicate times when adaptation of the RHF/PHF time constants is taking place.

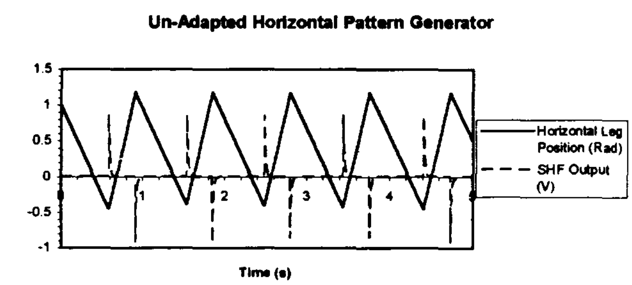

Figure 5 - The output of the horizontal leg position integrator and the slope neuron high-pass filter. The leg does not reach the PEP because time constant of the RHF is too small. The leg exceeds the AEP because the time constant of the PHF is too large.

Additional aspects of the simulation of figure 5 are shown in Figure 6 and 7. Figure 6 shows the output of the RHF. In the absence of sensory influences the retraction phase would end when the RHF output decays to 0.5 V. However, because the PEP has not been reached the PEPS has an inhibitory effect on the PMN and serves to extend the retraction phase. Because the PEPS output is less than zero when the SHF output pulses positive the time constant of the RHF is increased.

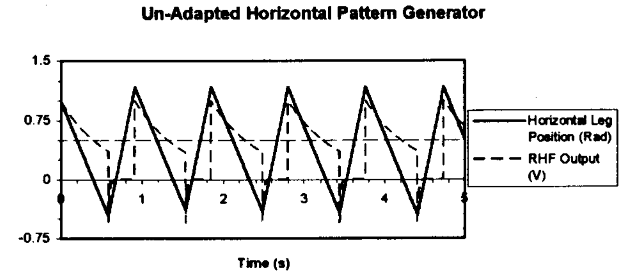

Figure 6 - The output of the retraction high-pass filter (RHF). The output of the RHF decays to less than 0.5 V due to the influence of the PEPS which is inhibiting the protraction motor neuron. The horizontal leg position and a dashed line at 0.5 V are shown for reference.

A complementary effect can be seen in figure 7 which shows the output of the PEPS. When the AEP is exceeded, the output of the AEPS becomes positive which inhibits the RMN and excites the PMN. This has the effect of shortening the protraction phase and decreasing the PHF time constant.

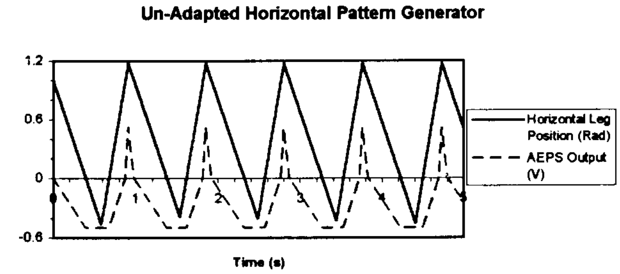

Figure 7 - The output of the anterior extreme position sensor (AEPS). The AEPS output exceeds 0 V when the leg position exceeds the AEP and causes the leg to begin a retraction phase. The horizontal leg position is shown for reference.

Figure 8 shows the time trajectories of the high-pass filter decay times. The decay time is as function of the filters time constant and is defined as the time required for the step response to decay to 1/2. It can be seen that the adaptation is complete within 25 seconds. The RHF decay time converges to 0.8 seconds and the PHF decay time converges to 0.4 seconds. These are the expected values for the decay times given the values of RS, PS, PEP and AEP used in the simulations.

Figure 9 shows the horizontal leg position integrator output, the PHF output and the AEPS output after adaptation of the time constants has converged. It can be seen that the motion of the leg is now between the PEP and the AEP. At the time of protraction-retraction transitions the output of the PHF is 0.5 V and the AEPS output reaches 0 V.

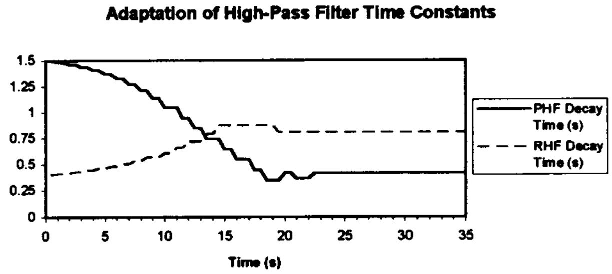

Figure 8 - Time trajectories of the protraction and retraction high-pass filter decay times. The RHF decay time converges to 0.8 s and the PHF decay time converges to 0.4 s.

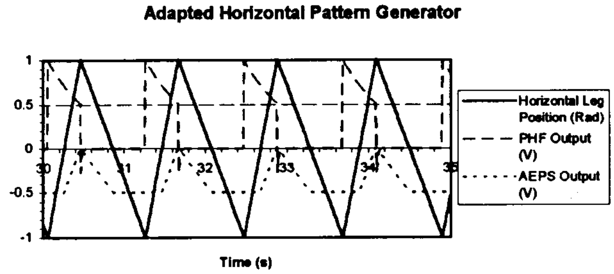

Figure 9 - The outputs of the leg position integrator, the posterior high-pass filter and the anterior extreme position sensor. Leg motion is between the PEP and the AEP. The PHF decays to 0.5 V and the AEPS output is 0 V at the phase transitions. A dashed line at 0.5 V is shown for reference.

2. *Non-Ideal Leg Controller*

The preceding simulations have shown that the pattern generator is capable of adapting the high-pass filter time constants when the leg position exactly matches the leg position integrator. In reality this will not be the case and the leg position will differ from the integrator output.

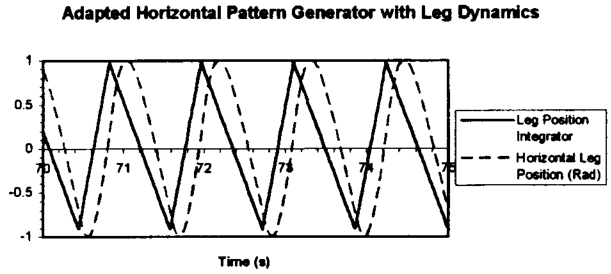

Figure 10 - The output of the horizontal leg position integrator and the actual horizontal leg position. The pattern generator has adapted to maintain the actual leg position between the AEP and the PEP.

Figure 10 shows the output of the leg position integrator and the actual leg position when the leg dynamics and controller are considered to be non-ideal. The position control system and leg dynamics are a second order model of a dc servo motor controlled using state feedback techniques. The poles of the closed loop system have been placed at $\lambda_1=\lambda_2=-10$. From figure 10 it can be seen that the time constants of the RHF and PHF have been adapted such that the actual leg position varies between the AEP and the PEP.

Adapted Horizontal Pattern Generator with Leg Dynamics

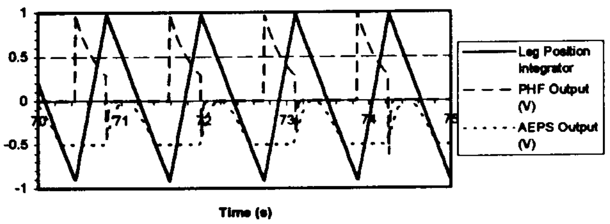

Figure 11 - The outputs of the leg position integrator, the posterior high-pass filter and the anterior extreme position sensor. A dashed line at 0.5 V is shown for reference.

Figure 11 shows the output of the PHF and the AEPS during the simulation from figure 10. The output of the AEPS is now reflective of the actual leg position and therefore is rounded and time delayed as compared to figure 9. Another effect of the leg dynamics is that the output of the PHF decays to less than 0.5 V before the RMN begins to fire. This effect is caused because the actual leg position lags the leg position integrator output. The leg dynamics have a similar effect on the RHF and PEPS outputs.

IV. Vertical Leg Motion Pattern Generator:

A. The Pattern Generator:

The elevation and depression phases of the leg motion are controlled by the vertical motion pattern generator shown in Figure 12. The vertical motion pattern generator is an extension of the reciprocal inhibition network which creates a four phase oscillation. The command neuron shown in figure 2 also synapses on each of the neurons in figure 12 but is not shown to simplify the figure. Similar to the horizontal pattern generator the duration of firing for each neuron, in the absence of sensory input, is determined by the time constants of the high-pass filters.

Four phases are required in the vertical pattern generator to allow the elevation and depression phases to overlap the protraction phase in an efficient and natural manner.[14] The protraction and elevation phases begin at the same time and the depression phase begins before the retraction phase. Figure 13 shows this relationship between the horizontal and vertical phases of leg motion. The neurons which control each phase of the leg motion are also indicated in figure 13.

B. Sensory Influences:

Sensory influences in the vertical pattern generator serve three purposes: synchronization with the horizontal pattern generator, invocation of searching mode behavior and limiting the vertical motion of the leg. Synchronization with the horizontal pattern generator is achieved by making the firing of the LMN dependent upon the output of the slope neuron (see figure 4.) This dependency ensures that the protraction and elevation phases begin in unison.

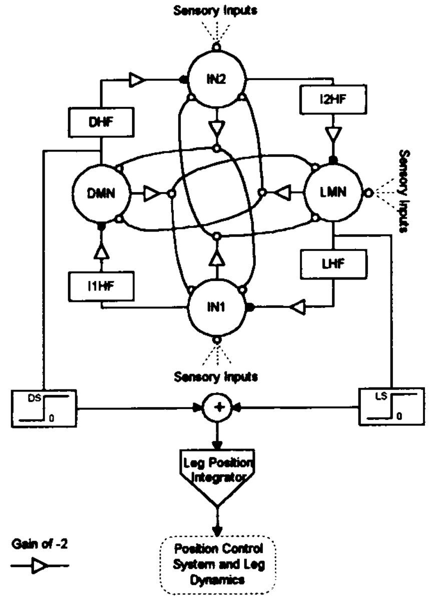

Figure 12 - The pattern generator for the control of vertical motion in the single leg. LMN:=Levator motor neuron, IN1:=Interneuron one, DMN:=Depressor motor neuron, IN2:=Interneuron two. DS and LS are system parameters and are measures of the elevation and depression speed of the leg. The command neuron in from figure 2 also synapses on each of the neurons in this pattern generator.

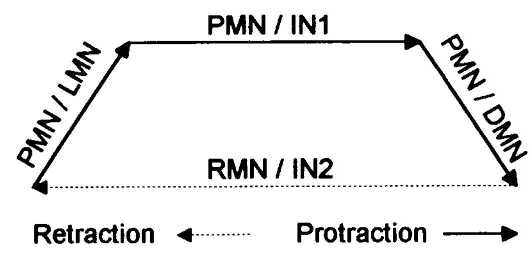

Figure 13 - Relationship between the horizontal and vertical phases of leg motion. The neurons which control each phase of motion are indicated.

Searching mode behavior occurs when a leg is in a retraction phase but does not contact the ground at the end of the depression phase. When in the searching mode a leg protracts to a position in excess of the AEP and makes repeated depression and elevation phases until contact with the ground is established. This behavior is useful when walking on uneven terrain and is intended to mimic a behavior found in the stick insect.[14] The circuit shown in figure 14 generates the signal which invokes the searching mode. The ground contact sensor signals contact with the ground and is a thresholded function of the load torque about the ϕ axis of the leg joint. The output of the SMN excites the PMN inhibits the RMN causing a protraction. The SMN also causes the time constants of the high-pass filters I1HF and I2HF to become temporarily small (by using the filter reset switch) allowing the elevation and depression phases to follow each other in rapid succession.

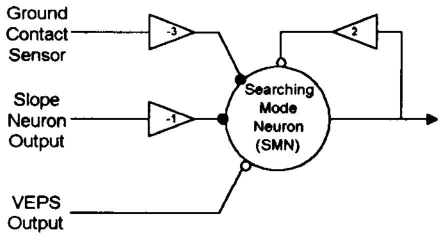

Figure 14 - Circuit for generation of the searching mode signal. Searching mode behavior occurs when a leg is in a retraction phase but does not contact the ground at the end of the depression phase.

Two antagonistic extreme position sensors, the dorsal extreme position sensor (DEPS) and the ventral extreme position sensor (VEPS), are used to limit the vertical motion of the leg. The DEPS and VEPS have a response to the legs vertical position identical to the response of the AEPS and PEPS to horizontal leg position (c.f. figure 3.) The DEPS has a bi-directional synapse on IN1 which, when the dorsal extreme position (DEP) is exceeded, causes IN1 to fire and inhibit the LMN. The VEPS has a bi-directional synapse on IN2 which causes IN2 to fire and inhibit the DMN when the ventral extreme position is exceeded.

C. Adaptation Mechanisms:

The adaptation mechanisms in the vertical pattern generator are very similar to those used in the horizontal pattern generator. They are sensory based and use a momentum learning rule. The adaptation of the LHF and DHF time constants is exactly analogous to the adaptation of the RHF and PHF time constants. The adaptation mechanism for the LHF or RHF is initiated when the leg stops its elevation or depression phase respectively. Cessation of elevation or depression of the leg is detected by a slope neuron circuit similar to the one in figure 4 with input provided by the vertical leg position. If the DEPS output is greater than (less than) 0 V at the end of elevation the LHF time constant is decreased (increased). If the VEPS output is greater than (less than) 0 V at the end of a depression phase the DHF time constant is decreased (increased).

The time constant for the I2HF will be identical to the time constant for the RHF (see figure 13.) Therefore, the time constant for I2HF is simply set to the same value as the RHF time constant. Adaptation in the I1HF must be performed to ensure that the leg contacts the ground at approximately the same time a retraction phase begins. To do this the time constant of I1HF is modified when a protraction to retraction transition takes place. If the VEPS output is greater than (less than) 0 V when a retraction begins the time constant of the I1HF is decreased (increased).

D. Simulation Results:

Simulations of the horizontal and vertical pattern generators have shown that the adaptation mechanisms enable the pattern generators to produce coordinated leg movements. These simulation are performed with RS=2.5 rad/sec, PS=5.0 rad/sec, LS=DS=10.0 rad/sec, PEP=-1.0 rad, AEP=1.0 rad, VEP=-0.5 rad and DEP=0.0 rad.

Figure 15 shows the output of the horizontal and vertical leg position integrators prior to any significant adaptation. The initial values of the high-pass filter time constants have been intentionally chosen to give uncoordinated movement. Figure 16 shows the actual leg positions corresponding to the integrator outputs of figure 15. The horizontal and vertical motions of the leg are clearly uncoordinated. However, the beginning of each protraction phase in figure 16 is accompanied by the start of an elevation phase. This is due to the influence of the horizontal leg slope neuron (see figure 4) on the LMN. The phase space plot of the vertical leg position versus the horizontal leg position shown in figure 17 emphasizes the uncoordinated quality of the leg movements.

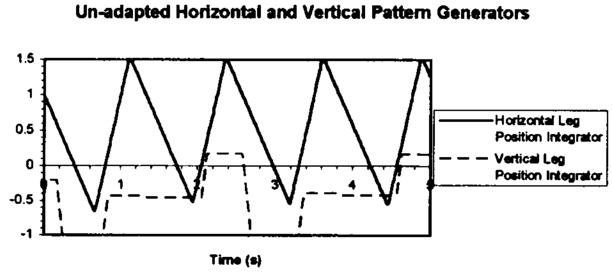

Figure 15 - Output of the horizontal and vertical leg position integrators prior to convergence of the time constant adaptation.

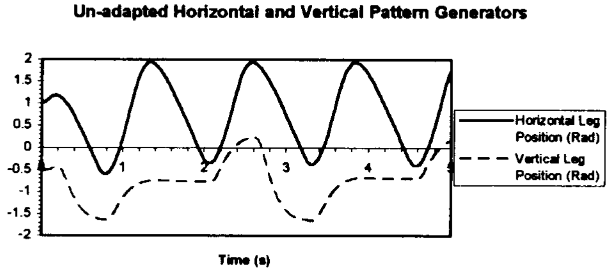

Figure 16 - The actual horizontal and vertical leg positions prior to convergence of the time constant adaptation.

Figures 18 and 19 illustrate the effectiveness of the adaptation mechanisms. Figure 18 shows the horizontal and vertical leg positions after the time constants have converged. The horizontal leg motion is clearly between the AEP and the PEP, likewise the vertical leg motion is between the DEP and the VEP. The onset of elevation still occurs in unison with the beginning of protraction. The adaptation has also ensured that the leg has been depressed prior to the start of a retraction. Figure 19 shows the vertical and horizontal leg positions in the phase space and clearly illustrates the coordinated motion of the leg.

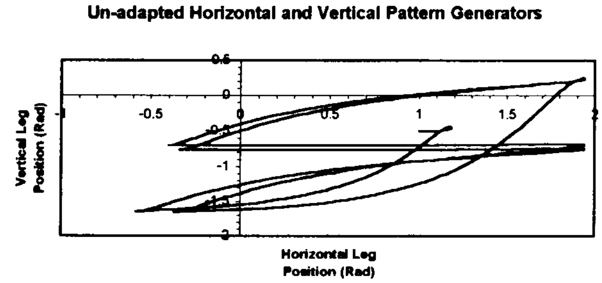

Figure 17 - The actual horizontal and vertical leg positions in the phase space prior to convergence of the time constant adaptation.

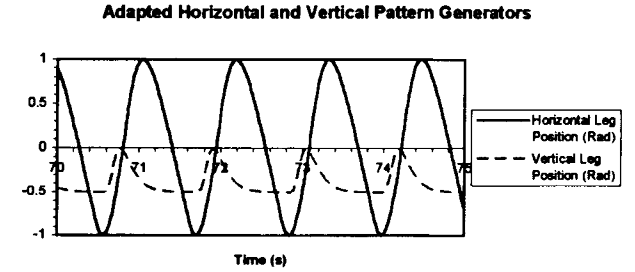

Figure 18 - The actual horizontal and vertical leg positions after convergence of the time constant adaptation.

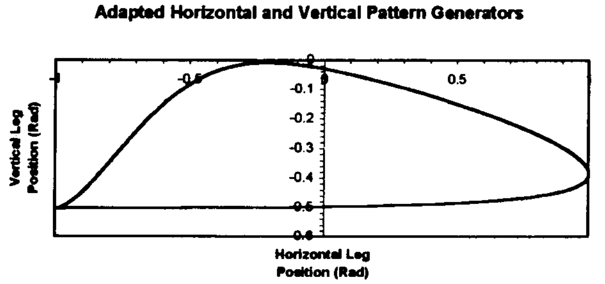

Figure 19 - The actual horizontal and vertical leg positions in the phase space after convergence of the time constant adaptation.

V. Coordination of Multiple Legs:

A design for the interconnections which create coordination between the pattern generators of multiple legs has been tested. The connections are heavily based upon the work of Beer et al., Cruse, Dean and Bassler on the interactions between the legs in crustacea and in the stick insect.[15] A model described by Grahm which produces a continuous range of gaits by coupling relaxation oscillators through threshold modification is also used.[16]

The coordination is established by making an inhibitory connection between the protraction neurons of adjacent legs. The connections are made both along the body and across the body. Figure 20 shows the connections that are established between the protraction neurons. These connections are sufficient to ensure that no two adjacent legs will protract simultaneously. To ensure stable gaits at all walking speeds the thresholds of the extreme position sensors are larger for the middle legs than the front legs and yet larger for the back legs. This gradient ensures that the gait progresses smoothly from the metachronal wave gait to the synchronous pair gait and finally to the tripod gait.[17] (See Wilson for a good review of hexapod gaits.[18]) The use of the coordinating mechanism also required the adaptation mechanisms, discussed above, to be modified to account for non-sensory influences.

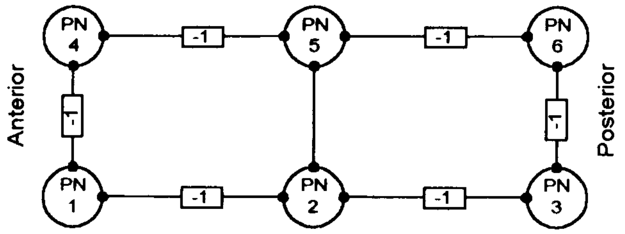

Figure 20 - Connections between the six protraction neurons which produces the coordination of the six legs.

Figure 21 shows the horizontal leg position for six legs coordinated in the synchronous pair gait with a retraction speed of 2.5 rad/second. Figure 22 shows the legs coordinated in the alternating tripod gait with a leg retraction speed of 5.0 rad/second. In each case the gait emerged from uncoordinated stepping as a result of the adaptation and connections between the legs.

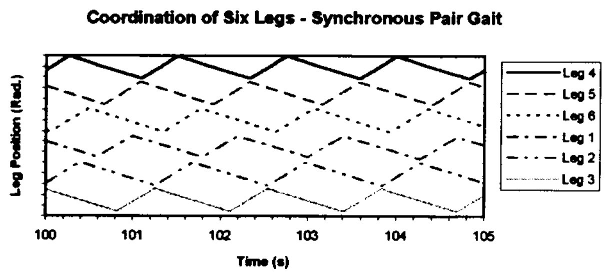

Figure 21 - Coordination of the legs into the synchronous pair gait at a leg retraction speed of 2.5 radians/second. The vertical scale must be interpreted relative to the trace for each leg.

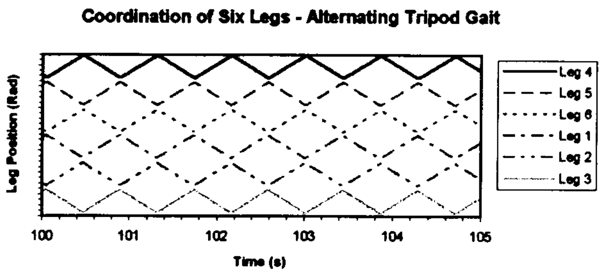

Figure 21 - Coordination of the legs into the alternating tripod gait at a leg retraction speed of 5.0 radians/second.

VI. Discussion:

A neural architecture for the adaptive control of leg coordination of a hexapod robot has been presented. The architecture has incorporated adaptability in a distributed way at a very low level. This adaptation has been shown to be capable of coordinating horizontal and vertical leg movements in the presence of non-ideal position control systems. Preliminary results show that the architecture is also able to coordinate movements between multiple legs to establish the tripod gait.

There are several issues that have yet to be addressed by this model. Walking at various speeds introduces the need for an associative memory to maintain a pairing between walking speeds and the set of time constants that are appropriate. Because the time constants are a smooth function of walking speed traditional neural network techniques may be used to approximate this mapping.

The mapping network for the time constants may also be extended to include other appropriate inputs. For example turning is accomplished by increasing the RS parameter for the legs on the outside of the turn and decreasing RS for legs on the inside of the turn. Therefore, information related to turning will be a valuable input to the mapping network. Other sensory inputs of interest may be the pitch and roll of the robot.

Including distributed adaptability at a low level as has been done here has potential positive implications for the design of autonomous robot systems. Low level distributed adaptation in behaviors such as walking or grasping ensures constancy in performance of these behaviors. This constancy not only holds across changes in the environment but also across changes in internal dynamics. Such a constancy allows higher levels of control to issue commands like walk and grasp with a high degree of certainty that they will be executed successfully.[19] Therefore, cause and effect mappings between high level commands (i.e. walk/grasp) and their effects on the environment (i.e. movement of self/movement of an external object) become more deterministic. The more deterministic these relationship become the easier it is to design controllers for higher level behaviors.[20]

References:

[1] J. S. Altman, J. Kien, "New Models for Motor Control", *Neural Computation 1*, 1989, pp. 173-183.

[2] R. A. Brooks, "A Robust Layered Control System For A Mobile Robot", *IEEE Journal of Robotics and Automation*, Vol. RA-2, No. 1, March 1986, pp. 14-23.

[3] A. Selverston, "Are Central Pattern Generators Understandable?", *The Behavioral and Brain Sciences*, Vol. 3, 1980, pp. 535-571.

[4] F. Delcomyn, "Insect Locomotion: Past, Present and Future", in *Insect Locomotion*, M. Gewecke, G. Wendler (eds.), Berlin, Germany: Verlag Paul Parey, 1985, pp. 1-18.

[5] U. Bässler, "Sensory Control of Leg Movement in the Stick Insect Carausis Morosus", *Biological Cybernetics*, Vol. 25, 1977, pp. 61-72.

[6] F. Delcomyn, "Neural Basis of Rhythmic Behavior in Animals", *Science*, Vol. 210, Oct. 31, 1980, pp. 492-498.

[7] R. Beer, H. Chiel, L. Sterling, "A Biological Perspective on Autonomous Agent Design", *Robotics and Autonomous Systems 6*, 1992, pp. 145-168.

[8] R. Beer, H. Chiel, R. Quinn, K. Expenschied, P. Larsson, "A Distributed Neural Network Architecture for Hexapod Robot Locomotion", *Neural Computation 4*, 1992, pp. 356-365.

[9] U. Bässler, "On the Definition of Central Pattern Generator and its Sensory Control", *Biological Cybernetics*, Vol. 54, 1986, pp. 65-69.

[10] R. Wong, K. Pearson, "Properties of the Trochanteral Hair Plate and its Function in the Control of Walking in the Cockroach", *Journal of Experimental Biology*, Vol. 64, 1976, pp. 233-249.

[11] U. Bässler, *Neural Basis of Elementary Behavior in Stick Insects*, Berlin, Germany: Springer-Verlag, 1983, pp. 93-94.

[12] G. Braught, S. C. A. Thomopoulos, "A Neural Architecture for Learning Hexapod Locomotion based upon Insect Neurophysiology", *IMACS Proceedings SPRANN '94*, (Lille, France), April 1994.

[13] J. Zurada, "Introduction to Artifical Neural Systems", St. Paul:West Publishing Co, 1992.

[14] U. Bässler, "The walking- (and searching-) pattern generator of stick insects, a modular system composed of reflex chains and endogenous oscillators", *Biological Cybernetics*, Vol. 69, 1993, pp. 305-317.

[15] H. Cruse, "Coordination of Leg Movement in Walking Animals", in *Proceedings of the First International Conference on Simulation of Adaptive Behavior: From Animals to Animats*, J. Meyer and W. Wilson eds., Cambridge:The MIT Press, 1991.

[16] D. Grahm, "Simulatoin of a model for the coordination of leg movements in free walking insects", *Biological Cybernetics*, Vol. 26, 1977, pp. 187-198.

[17] R. Beer, et. al., 1992.

[18] D. Wilson, "Insect Walking," Annual Review of Entomology, Vol. 11, 1966, pp. 103-122.

[19] S. C. A. Thomopoulous, G. Braught, "A Biologically Inspired Architecture of Machine Perception and Intelligent Control for Multi-Robot Coordination", Sumitted to 3rd IEEE Mediterranean Symposium on New Directions in Control and Automation, 1995.

[20] G. Braught, S. C. A. Thomopoulous, "Application of Modern Control Theory to the Distributed Control of an Artifical Superorganism", Technical Report, Decision & Control Systems Laboratory, The Pennsylvania State University, 1994.