Adaptive Optimal Locomotion of Snake Robot Based on CPG-Network Using Fuzzy Logic Tuner

Sh. Hasanzadeh
Mechanical Engineering Dept.
Ferdowsi University
Mashhad, Iran
shahirhasanzadeh@yahoo.com

A. Akbarzadeh Tootoonchi
Mechanical Engineering Dept.
Ferdowsi University of Mashhad
Mashhad, Iran
ali_akbarzadeh_t@yahoo.com

Abstract—**Periodic locomotion of animal bodies with large degrees of freedom is known to be realized by network of central pattern generators (CPGs) that are distributed in spinal cord (in vertebrates) or nerve cords (in invertebrates). In this paper, optimization of a controller for a snake robot locomotion based on CPG-network is presented. CPGs are modeled as nonlinear oscillators for each joint. The inter-joint coordination is achieved by altering the connection weights between joints. Genetic algorithm (GA) is used to optimize CPG parameters and connection weights in terms of moving speed. We proposed a new method that can be used as on line detection of changes in environmental conditions. Effect of friction coefficients on optimal parameters is next investigated. Results are utilized to design a fuzzy logic tuner with the goal of maintaining optimality of the locomotion while snake robot moves in different environmental condition (surfaces with different friction coefficients). Optimal CPG-network parameters are also obtained for snake robot with different numbers of links. Results indicate that the fuzzy rules can be expanded for snake robot with any numbers of links. This paper is a step towards designing an optimal CPG controller with improved environmental adaptability.**

Keywords—**centeral pattern generator, snake robot, serpentine locomotion, genetic algorithm**

I. INTRODUCTION

Snake robots are serially connected, multilink articulated mechanisms, which propel themselves by body shape undulations. Despite having challenges in the area of control and inefficiency in locomotion due to high friction snake robots have attracted the attention of researchers for applications not suitable for wheeled and legged robots. Applications such as ruins of collapsed buildings or narrow passages in search and rescue operations are good examples where snake robot may be used.

Snake robots are advantageous over wheeled vehicles due to their terrainability, high adaptability to environment (by using suitable locomotion modes) and increasing reliability due to their modular nature. However, the two main challenges of snake robots over wheeled mechanisms are difficulty in control of snake-like locomotion as well as their poor power efficiency. In this paper we contribute to both of the two disadvantages by presenting central pattern generator (CPG) based controller and applying GA to optimized CPG structure in terms of moving speed.

Locomotion control of snake robot has been addressed by many researchers. There are two main approaches in generating robot locomotion. The first approach uses kinematics and dynamics for entire robot body. Because of complexities of dynamic and kinematic models robot motion were limited to environments with known horizontal [1] or inclined [2] plane. As a result, snake robots cannot exhibit high environmental adaptability. This is in contrast to natural capabilities of living snakes.

Recently, the control methodology based on central pattern generator (CPG) is attracting a great deal of attention as a methodology to realize quick and adaptive motion generation of such robots having large degrees of freedom. CPG is a neural oscillator module that generates self-induced oscillation, and is found in spinal cords in living animals. Animals can naturally and quickly generate purposive rhythmic motion patterns. They do this by entrainment caused by inter-CPG interaction and sensory input from musculoskeletal system.

There are many researches to realize control of animal-like robots based on CPG-network model. Kimura et al [3], [4] realized adaptive dynamical walking of real quadruped robot using a CPG model. The CPG model was proposed by Matsuoka [5] and was also utilized for bipedal walking models by Taga et al [6].

Conradt et al [7] realized the traveling wave on a real snake-like robot by connecting CPGs in series. However, the dynamics of neural model in [7] is not dealt with and relationships between neurons are only regulated using simplified model. Crespi et al [8] proposed CPG based controller for amphibious snake-like robot and constructed an experimental model. Ma [9] proposed the control architecture for meandering locomotion based on CPG-network. He simulated this architecture with consideration of mechanical dynamics of a snake robot.

In this paper, we consider CPGs as nonlinear oscillators and find the optimal CPG-network parameters in terms of speed of a snake robot moving on surfaces with different friction coefficients. Next we propose a fuzzy logic tuner for self altering of CPG-network parameters to their optimal values.

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The rest of the paper is organized as follows. Section II describes dynamic consideration of the snake robot and friction model. Section III introduces CPG architecture and its features. Section IV describes how to find optimal CPG parameters using GA. Section V describes effect of changing environment and number of links on optimal CPG-network parameters. Section VI discusses environmentally adaptive snake robot locomotion and explains structure of the proposed fuzzy logic tuner. Finally, section VII concludes the paper and summarizes the future work.

II. HYPER REDUNDANT SNAKE ROBOT MODEL

In this paper we consider a planar 5 link snake robot with dynamically identical links having no wheels. The robot model is composed of serially connected links. Between every two links, a one-dimensional joint rotating on vertical (yaw) axis is located. Similar to real life snakes, friction force between the robot body and the environment is large in normal direction and small in tangential direction. This is commonly realized using passive wheels in snake robots.

Dynamic analysis of such a mechanism, moving on a plane with friction has already been studied by several researchers [10] and [11]. We implement the dynamics using MATLAB SimMechanics in our computer simulations, for which a snapshot is given in Fig. 1.

In our simulations, we consider a simple viscous friction model. Friction force is modeled by the following equations

$$f_{t,i} = -C_t m_i v_{t,i} \tag{1}$$

$$f_{n,i} = -C_n m_i v_{n,i} \tag{2}$$

Where Ct and Cn are normal and tangential viscous friction coefficients. Suffix i indicates corresponding i-th link, $f_{t,i}$ and $f_{n,i}$ are friction forces in tangential and normal direction respectively, m_i is mass of i-th link, $v_{t,i}$ and $v_{n,i}$ are velocities of center of mass of the i-th link.

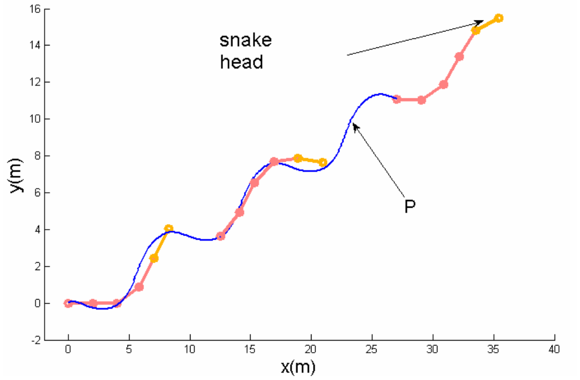

Figure 1. A snapshot from the Simmechanics software demonstrating a 5-link planar snake robot moving with serpentine gait. Links are similar with mass of 1 Kg, length of 2 m and inertia of 0.33 Kg.m^2. P is path followed by tail.

III. CPG CONTROL OF LOCOMOTION

The CPGs found in vertebrates are composed of neural oscillators. However, the real neurons have very complicated behaviors. It is very difficult to build and simulate a mathematical model as close as possible to the real life CPGs. Here we use nonlinear oscillators as building blocks for constructing CPGs. This model of CPG was applied to a biomimetic robotic fish by Zhao et al [12] to simulate swimming and develop multi-modal locomotion of the robot.

$$\begin{aligned} \Delta\theta &= \theta - \bar{\theta} \\ \dot{v} &= w(v - \Delta\theta) - \frac{v}{A}(v^2 + \Delta\theta^2) \\ \dot{\theta} &= w(v + \Delta\theta) - \frac{\theta}{A}(v^2 + \Delta\theta^2) \end{aligned} \tag{3}$$

where θ is a state variable and denotes the desired joint angle, v is another state variable, w is a positive constant that controls both the oscillatory frequency and amplitude, A is a positive constant adjusting only the amplitude and $\bar{\theta}$ is a parameter that allows shifting of the $\tilde{\theta}$ (particular solution) values.

Equations (3) have two particular solutions, one is zero (0,0) which is an unstable fixed point. The other is a stable limit cycle which has a sinusoidal value with amplitude $\sqrt{Aw}$ and period $2\pi/\omega$. θ will converge to the particular solution of

$$\tilde{\theta} = \sqrt{Aw}\,\sin(wt + \varphi) + \bar{\theta} \tag{4}$$

from any initial condition (θ0,v0) (except zero (0,0) in the phase plane). φ is determined by the initial states.

IV. UNDULATORY GAIT GENERATION

Equations (3) provided oscillation for one joint. A specific gait pattern will be obtained by coupling several oscillators together, in our case one oscillator per joint. State equations of the connected CPGs are as follows

$$\begin{aligned} \Delta\theta_i &= \theta_i - \bar{\theta}_i \\ \dot{v}_i &= w(v_i - \Delta\theta_i) - \frac{v_i}{A_i}(v_i^2 + \Delta\theta_i^2) + \sum_{j=i-1,i+1}(a_{ij}\theta_j + b_{ij}v_j) \\ \Delta\dot{\theta}_i &= w(v_i + \Delta\theta_i) - \frac{\theta_i}{A_i}(v_i^2 + \Delta\theta_i^2) \end{aligned} \tag{5}$$

where α_{ij} and b_{ij} are the connection weights (synaptic weights) between the i-th and j-th joints. Because only connected joints have impact on each other, j could be either i-1 (the frontal joint) or i+1 (the latter joint). A stable travelling wave from head to tail can be obtained by modulating the coupling coefficients a_{ij} and b_{ij}, which determine the phase-lag or phase-lead relationship between connected joints.

Even though snakes are so diversified, there generally exist four gliding modes (gait): 1) Serpentine; 2) Rectilinear; 3) Concertina and 4) Sidewinding. The serpentine movement shown in Fig. 1 is the movement that we can see in almost all snakes. It is a gliding mode whose characteristic is that each part of the body makes similar tracks. The most straightforward way to generate serpentine gait in a serial chain with *n* links is by having the joint angles vary sinusoidally with a common frequency and a constant phase lag between consecutive joints. The undulatory motion can then be imitated by changing the relative angles of the snake robot in the following manner:

$$\theta_i = \alpha \sin(\omega t + (1-i)\beta) + \gamma \quad (i = 1,2,\dots n) \qquad (6)$$

Where α is he maximum angular deflection for each joint, β is the phase difference of any two adjacent relative angles, γ is the angular offset that provides a means for steering the mechanism.

Structure of the proposed connected CPGs is schematically shown in Fig. 12. The block named fuzzy logic tuner will be explained in section VII. CPG-network parameters which consist of CPG parameters ($A1$ - $A4$, w, $\overline{\theta}_1$ to $\overline{\theta}_4$) and synaptic weights ($a_{i\,i-1}$ and $b_{i\,i-1}$.) are selected in order to generate joint angle trajectory similar to (6).

A set of solutions that propagate a serpentine wave from head to tail have been obtained in our simulation. An example of such solutions θ_1 to θ_4 to generate a serpentine wave is illustrated in Fig. 2, where $a_{i\,i-1}=1$, $b_{i\,i-1}=1$, $A1=A2=A3=A4=1$, $w=1$ and $\overline{\theta}_1 = \overline{\theta}_2 = \overline{\theta}_3 = \overline{\theta}_4 = 0$. Time range from 0 sec to 35 sec is selected. Period and amplitude are modulated by doubling the parameters *w* and *A* of all CPGs at time *t=25* sec. As shown in Fig. 2, each joint can smoothly adapt to the abrupt changes of oscillatory frequency and oscillatory amplitude determined in the CPG model. This feature will be utilized in section VII to construct a fuzzy tuner for tuning CPG parameters while robot is moving.

V. OPTIMIZATION USING GENETIC ALGORITHM

GA can deal with optimization of complicated systems by simply simulating system behavior and applying an evaluation index. Therefore we use GA in order to find optimal CPG-network parameters in terms of speed. In this section we consider a general form of the proposed CPG-network for a 5-link snake robot. We show that the highest speed is achieved by CPG-network parameters which generate a motion similar to serpentine gait.

GA is an optimization method imitating biological evolution. The target of optimization (CPG-network parameters $A1$~$A4$, a21, $a32$, $a43$, $b21$, $b32$, $b43$) are coded as chromosome and called genotype. Phenotype is the result of decoding of genotype (resultant robot locomotion, in this study) and is evaluated by the use of computer simulations.

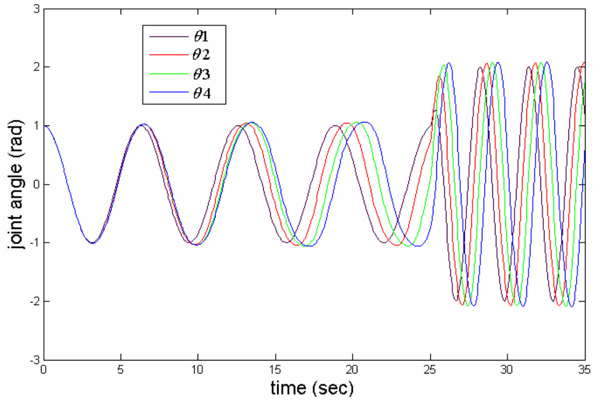

Figure 2. Oscillatory angles θ_1 (t) to θ_4 (t) of four joints based on CPGs.

Genotypes with lower evaluation in gene pool will be deleted from the pool and remaining superior genotypes will succeed to next generation after being processed by genetic operators, i.e. mutation and crossover. By repeating this process, finally chromosomes with high quality can be derived. GA process steps are listed as follows:

Coding - As genotype, we code chromosomes by serially connecting parameters discretized into 16-bit integers within given ranges. The resultant lengths of chromosomes become 160-bit (total of ten CPG-netwrok parameters). At the first stage of GA, new chromosomes are created by randomly setting parameters within ranges given to each parameter.

Constraints - Because of mechanical limit of motor rotation angle, parameter $A1$~$A4$ is constrained to a maximum value of $\sqrt{A_i w} \le \theta_{\max}$ (i=1, 2,..4). Chromosomes not satisfying these values will be deleted and new random chromosome will be created.

Fitness Evaluating - Fitness function that should be minimized is the inverse of center of mass displacement, during simulation time (T_s). In addition to CPG-network parameters, fitness function depends on environmental condition, Ct and Cn. Therefore, initially, an assumed fixed value for Ct and Cn is selected and GA optimization is performed.

Based on the above-mentioned settings, we optimize CPG-network parameters. Other GA parameters are set as follows: Population $N=10$, Crossover probability $P_c= 0.5$, Mutation probability $P_m=.01$, Number of generations $G= 200$.

Development of fitness value is shown in Fig. 3. We find CPG-network parameters for given $\omega=\pi$ rad/s, $\theta_{max}=\pi/2$ and T_s=50 sec. Environmental conditions is parameterized by parameter C_t/C_n $=0.01$. As shown in Fig. 3, After 200 generations, best fitness value converges to 4.778. Best individuals corresponding to the best fitness value are $A1$=0.178, $A2$=0.216, $A3$=0.096, $A4$=0.009, $a21$=4.132, $a32$=2.061, $a43$=1.561, $b21$=6.229, $b32$=4.821, $b43$=.0045. Therefore, using these parameters snake robot can achieve maximum speed of 4.18 m/sec.

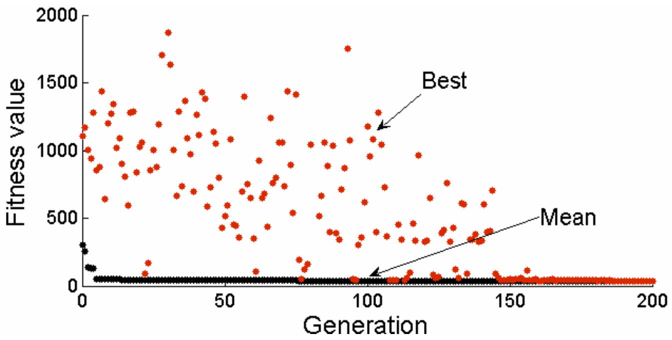

Figure 3. Development of the best and mean values of fitness for every generation.

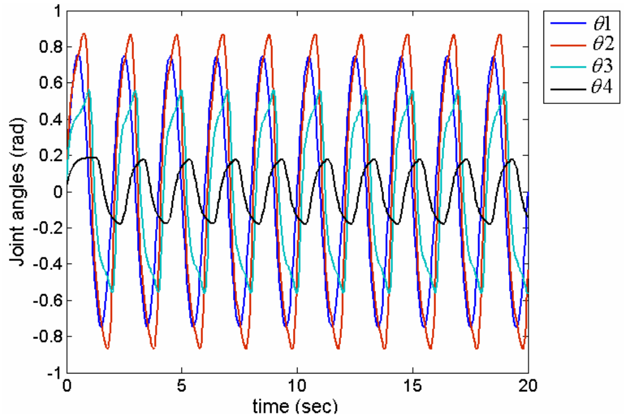

Figure 4. Optimal oscillatory angles θ_1 (t) to θ_4 (t) of 5-link robot.

Fig. 4 shows joint angle trajectories generated by optimized CPG-network. As it is illustrated in this figure, generated trajectories are in sinusoidal form with phase shifts and are similar to commonly used serpentine gait joint angles trajectories (6). Therefore we can conclude that the highest speed for a two dimensional snake robot can be achieved by using serpentine gait.

VI. EFFECT OF FRICTION COEFFICIENTS ON OPTIMIZED CPG-NETWORK PARAMETERS

In real world application of snake robot, environment conditions are not constant therefore snake robot should be adaptive to different environments. In this section we consider a 5-link snake robot and investigate the effect of environmental conditions on optimal CPG-network parameters. We use ratio of normal to tangential friction coefficient as a means to parameterize environmental conditions (similar to [10]). Next, we run GA optimization codes for different environmental conditions. We adjust the GA parameters settings similar to section V except number of CPG-network parameters are six (*A*1, *A*2, *A*3, *A*4, *a*, *b*). This means that we use equal value of *"a"* for all a_{ij} and equal value of *"b"* for all b_{ij}. This is because these parameters do not have a considerable effect on maximized speed. Furthermore, using equal values result in significant decrease in optimization run time.

Fig. 5 shows effect of environmental conditions on *A1~A4*. As illustrated in this figure optimal *A1~A4* increases when Ct/Cn increases. These simple rules will later be used as a fuzzy inference system of a fuzzy tuner.

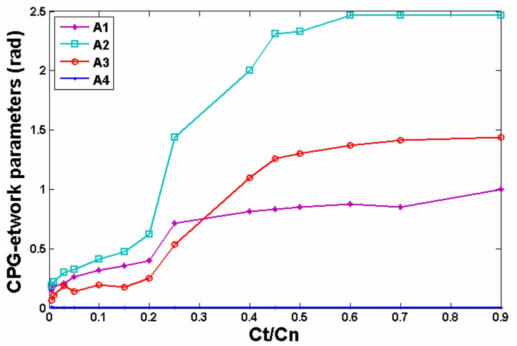

Figure 5. Effect of friction coefficients ratio on optimal CPG parameters (*A1~ A4*).

Fig. 6 shows effect of friction coefficients ratio on "*a*" and "*b*" parameters. As illustareted in this figure, optimal values of "*a*" and "*b*" parameters are approximately constant (with mean value of *a*=7.3 and *b*=8.3) with changes in environmental conditions. Maximum value of moving speed decreases when robot is moving on a surface with small ratio of friction coefficients (Fig. 7).

In order to show the generality of these results we repeat the above mentioned procedure for snake robot with different numbers of links. As an example, Fig. 8 and Fig. 9 show CPG parameters and synaptic weights, respectively versus ratio of friction coefficients for a 4-link robot. As illustrated in these figures optimal CPG parameters (*A*1 and *A*2) increase when Ct/Cn increases. It is also illustrated that Ct/Cn dose not have a considerable effect on optimal synaptic weights (*a* and *b*). These results are similar to results obtained for 5-link snake robot.

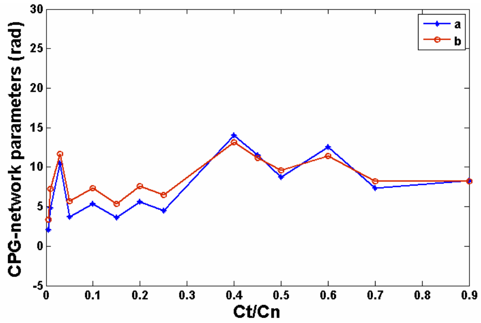

Figure 6. Effect of friction coefficients ratio on optimal synaptic weights (*a* and *b*).

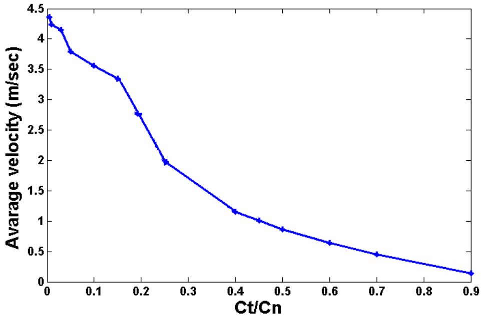

Figure 7. Effect of friction coefficients ratio on maximum velocity of the robot.

VII. ENVIRENMENTALLY ADAPTIVE LOCOMOTION

As mentioned in the previous section optimal CPG-network parameters depend on friction coefficients of the surface which snake robot moves on. Therefore CPG-network parameters which are optimal in specific environmental conditions do not produce optimal locomotion in another environment. In this section our objective is to maintain the optimality of the robot locomotion while its environmental conditions change.

We obtain environmentally adaptive locomotion by using a fuzzy logic tuner that adjusts CPG-network parameters so that they reach their optimal or near optimal values when environmental conditions change.

A. Detection of Change in envirenmetal Conditions

In order to design an adaptive tuner, we need to find a measurable parameter that can detect changes in friction coefficient of the surface which snake robot moves on. Automatic sensing of friction coefficient is very difficult to implement. Here we propose a method that can detect changes in value of friction coefficients. The significance of this method is that it can be used with a controller to provide instantaneous changes in environmental conditions.

We observed that amplitude of the input torque to joints change when robot environment conditions change. In addition this parameter can be easily sensed online while snake robot is moving. Therefore we use it as means of detection of changing of the environment.

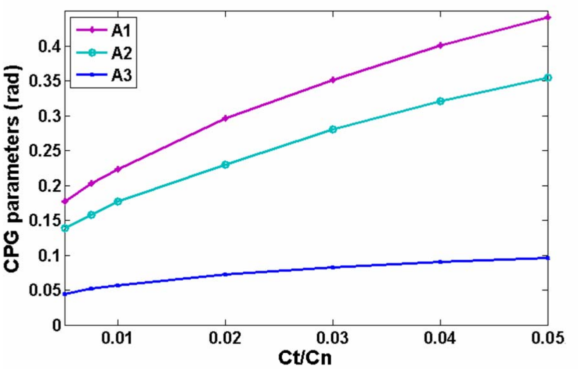

Figure 8. Effect of friction coefficients ratio on optimal CPG parameters (*A1~ A3*) for 4-link snake robot.

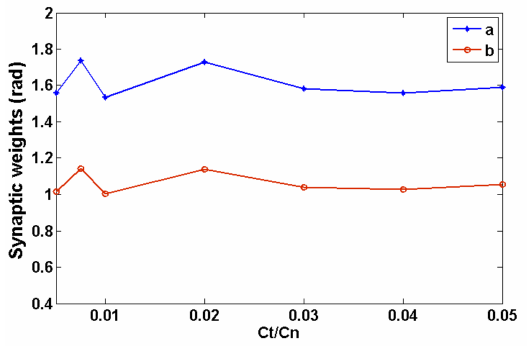

Figure 9. Effect of friction coefficients ratio on optimal synaptic weights (*a* and *b*) for 4-link snake robot.

Fig. 10 shows torque applied to the head joint when ratio of friction coefficient changes from .01 to .08 at time 10 sec and then to 0.04 at time 20 sec. It is illustrated that applied torque has a sinusoidal form with mean value of zero. Amplitude of the input torque increases when ratio of friction coefficient increases and vise versa. In the following section, these simple rules which are inherent in dynamics of the snake robot moving with serpentine gait is used as fuzzy inference system for a fuzzy logic tuner.

Fig. 11 shows amplitude of the input torque to all joints for a 5-link snake robot. As illustrated in this figure, relation between input torques and ratio of friction coefficients are similar for all joints. Therefore, one can select input torque of any joint as the detecting parameter for changes in environmental conditions. It is also possible to take advantage of sensor redundancy by measuring input torque of more than one joint. This will increase measurement reliability and results in more reliable system.

B. Fuzzy Logic Tuner

Because of inherent uncertainty of robot dynamics (its motion is highly related to friction coefficients of the ground) using of fuzzy logic tuner as a means to tune CPG-network parameters seems to be a proper approach.

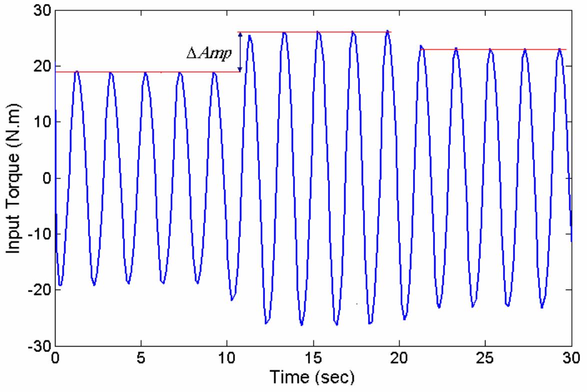

Figure 10. Torque applied to the head link joint while robot is moving using serpentine gait in an environment with changing friction coefiicients.

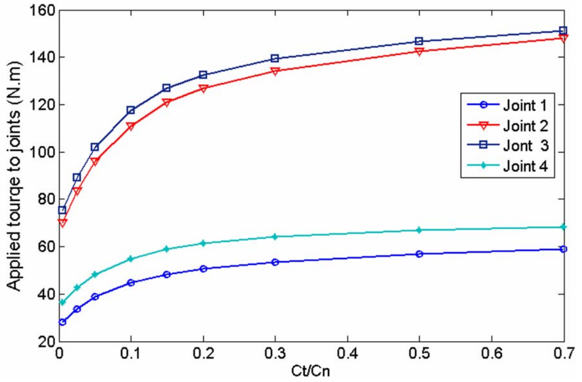

Figure 11. Input torque to joints of a 5-link snake robot moving with serpentine gait.

In addition to capability of dealing with uncertainty, fuzzy logic controllers (tuners in our case) can utilize linguistic rules to control (tune) a complicated dynamic system. Linguistic rules for fuzzy logic tuner can be obtained by observing the effect of friction coefficients ratio on optimal CPG- network parameters (Fig. 5 and Fig. 6) as well as effect of friction coefficients ratio on detecting parameter (applied torque). Considering the previous sections, the following observations can be stated:

-A1 increases as ratio of Ct/Cn increases. (Fig. 5)

-Amplitude of applied torque increases when Ct/Cn increases. (Fig. 11)

The two observations can be combined into one fuzzy logic rule

If change in value of input torque is big then A1 is big.

Similarly, we can obtain additional fuzzy rules for the remaining CPG-network parameters. As optimal synaptic weights are constant in any environmental conditions, only CPG-parameters are tuned Therefore, the number of fuzzy logic tuners is equal to the number of CPG parameters (4 separate fuzzy tuner for a 5-link snake robot – *A1~A4*).

Input to all these fuzzy tuners is change in amplitude of input torque (shown by ΔAmp in Fig. 10). In order to calculate ΔAmp, maximum amplitude of input torque for a specific number of cycles of motion is measured and compared with the previous value. Schematic view of the proposed fuzzy logic tuner is illustrated in Fig. 12.

Outputs of fuzzy tuners are changes in value of CPG-parameters (e.g. $\Delta A1$, $\Delta A2$, $\Delta A3$ and $\Delta A4$ for a 5-link snake robot). These values are added to the previous CPG-network parameters values to produce new CPG-network parameters values. New CPG-network parameters are near optimal parameters for the current environmental conditions.

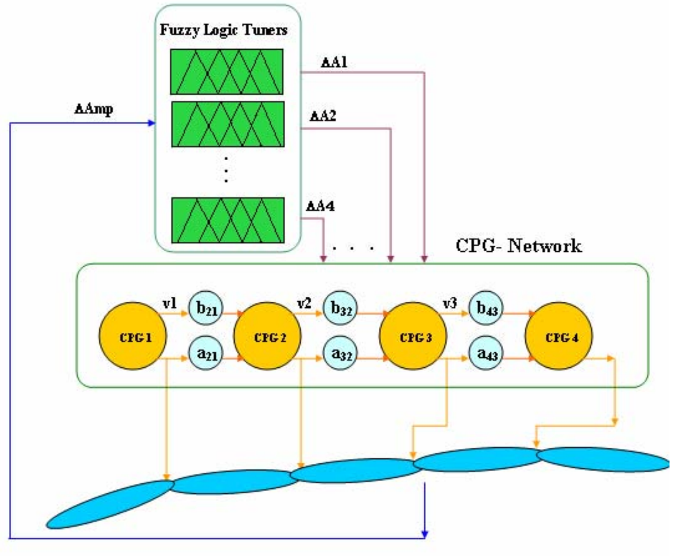

Figure 12. Relation among CPG-network, robot and fuzzy logic tuners.

VIII. CONCLUSION

In this paper, we utilized GA to optimize CPG-network parameters of a snake robot in order to achieve maximum robot speed. CPGs were modeled as nonlinear oscillators for each joint. Next, we found relations between optimal CPG-network parameters and environmental conditions for snake robot with different numbers of links. We proposed a new method that can be used with a controller to provide instantaneous changes in environmental conditions. This method senses changes in joint torques to detect changes in friction coefficients. Next we utilized relations between optimal CPG-network parameters and environmental condition as well as changes in joint torque and changes in friction coefficients to construct fuzzy rules for a fuzzy tuner. Lastly, we utilized the fuzzy tuner to tune CPG-network parameters during motion to achieve maximum robot speed. We also showed that the fuzzy rules can be expanded for snake robot with any numbers of links.

This paper is step toward designing an optimal CPG controller with higher environmental adaptability for snake robot. Future research will focus on developing adaptability and autonomy of snake robot, as well as constructing an experimental test bed to verify the theoretical results.

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