TRAJECTORY PLANNING AND CONTROL FOR A HUMAN-LIKE ROBOT LEG WITH COUPLED NEURAL-OSCILLATORS

Li Liu, Andrew B. Wright and Gray T. Anderson

Applied Science Department
University of Arkansas at Little Rock
Little Rock, AR 72204

Abstract: The control of legged robots can be inspired from how biological systems (living creatures) control movements. In this paper, an oscillator-based gait rhythm generator is designed, and a computed torque controller implements the movement of a four-link robot leg. The coupled oscillator network generates trajectories of the hip, knee, and ankle joint angles resulting in a gait similar to that of human. Oscillator parameters and coefficients are tuned to achieve human-like trajectories. The desired torque applied to each joint is generated by the computed torque controller according to reference signals from the gait rhythm generator and feedback signals from the joints. Oscillator based control strategies are implemented and tested in simulation on a PC system. The equation of motion (EOM) of a multi-degree of freedom, four-link robot leg has been derived by Newton-Euler method to validate and evaluate the performance of gait rhythm generator and torque controllers.

I. INTRODUCTION

Recently, intensive studies have been focused on walking robots. Compared to traditional wheeled robots, walking robots will be able to handle uneven terrain and soft ground in difficult conditions where wheeled robots cannot go. Furthermore, one can take the advantages of biologically inspired control strategies and apply the control scheme to robots through observing how living creatures control their movements.

Usually, two-legged robots are designed according to the human skeleton and controlled according to human behaviors. This encourages many researchers to investigate the basic human movements and try to apply the human behavior to robots. Today, the notion of central pattern generator (CPG) has been developed based on living organisms to generate the human-like gait rhythm.

The kernel of CGP is the rhythm generator, which uses the coupled neural-oscillator to produce the rhythmic output. The newest research of biologically inspired walking machine was presented by Berns et.al (1999). They used the oscillator originally proposed by Brown (1914) to generate oscillatory behavior, which possibly imitates mammal-like walking gait. A single leg control was described by Wadden and Ekeberg (1998) using a non-spiking neuron model as the first step in the process of modeling and building a fast and dynamically stable quadruped. Pribe et.al(1997) presented a neural control of inter-limb using Ellisa_Grossberg oscillator for a four-leg walking machine. This neural control actually was a body gait control that the oscillator devoted to movement gait with stick legs without joints. Zielińska (1996) used the Van Del Pol (VDP) oscillator as the gait rhythm generator for a two legged walking machine. There was a coupled neural-oscillator on the hip and knee joint. Taga (1995) used Matsuoka oscillator on a bipedal robot. The gait pattern was represented as a cyclic sequence of six states. Collins and Richmond (1994) made a comparison of three different oscillator models: the Stein neuronal model, the VDP model, and the FitzHugh-Nagumo model. However, their oscillators were only used for inter-limb control on a quadruped machine similar to Pribe (1997).

Most models have focused on either properties of the neural-oscillator or control architectures of inter-limb of walking machine. Few of them reported an intensive investigation on the human-like robot leg with hip, knee, and ankle joints. There are few applications of the gait rhythm generator on a human-like robot leg due to the lack of appropriate walking machine prototype and corresponding equation of motion (EOM).

This paper will present the movement properties of a human-like robot leg. The coupled neural-oscillator serves as gait rhythm generator to obtain nearly biological pattern of walking trajectories. Desired trajectories are fed into a computed torque controller, which generates desired joint torques. The joint torques are fed into the dynamic model. The equation of motion of a complex, multi-degree of freedom, human-like robot leg has been derived by Newton-Euler method to validate and evaluate the performance of gait rhythm generator and controller. Figure1 shows the general biologically inspired control structure of a walking robot.

The main advantage of using the coupled neural-oscillator is that the desired trajectories are reactive to the dynamics of the system (Williamson 1999). The desired trajectories are generated by the oscillators through a complex neural network and are synchronized with the system motion. The more advantages can be exhibited in multiple joint control, which has considerable dynamic complexity. If one uses the classic robotic control approach to generate the trajectories, the calculation will begin from body movement, foot point trajectories, inverse kinematics, and finally to joint angle parameters. This process is complex and time consuming so that some effective algorithms and compromises have to be considered to apply the control scheme to the real-time walking robot system. On the other hand, for a fix CPG system, only a wide rang of oscillator parameters are required to generate the various tasks such as walking, running, and jumping.

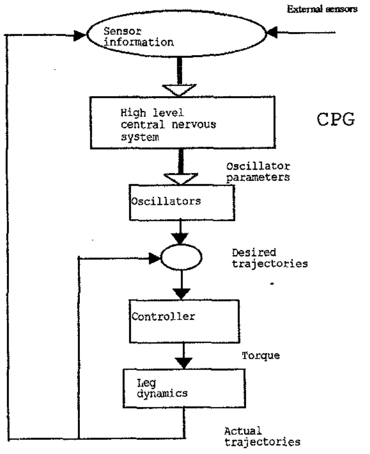

Figure1. Robot leg control system with a CGP network.

II. GAIT RHYTHM GENARATOR

1.Neuro Oscillator

In this paper, a four-link, human-like, single robot leg is investigated. Trajectories of the hip, knee, and ankle joint angles are produced, resulting in a gait pattern similar to that of human. Since the robot leg is symmetrical and similar in many configurations, the concentrated studies on a single leg are valuable and can be applied to bipedal or quadruped walking machines with body and inter-limb controller.

Several oscillators have been used as gait rhythm generators. However, the application on a four-link robot leg with a full coupling on the hip, knee, and ankle has not been done. A simple and well-known neural network model is investigated as the gait rhythm generator. This neural-oscillator model, which was used extensively in physiological modeling studies, originally stemmed from well-known Van Del Pol equation and was redefined by Bar and Hemami (1987). The general equation of Van Del Pol oscillator can be described by following equations.

$$\ddot{X}_i - u_i(p_i^2 - X_{ai}^2)\dot{X}_i + g_i^2 X_{ai} = m_i \qquad (1)$$

where i is the oscillator index and u, p, g, m are the parameters that influence the properties of oscillators.

The value of X is a function of the time corresponding to ith joints. Xai is the same signal as X affected by the coupling equation.

$$X_{ai} = X_i + \sum \lambda_{ji} X_j \qquad (2)$$

where λ_{ji} is a coupling term that represents the strength of oscillator j's effect on oscillator i's.

To obtain the human-like walking trajectory, the oscillator output should be scaled and offset by k and θ to present the joint position q adequately.

$$q_i = k_i X_i + \theta_i \qquad (3)$$

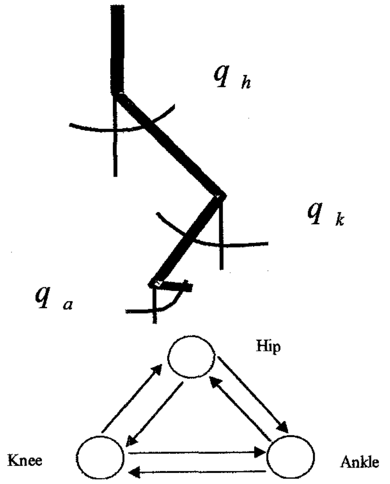

Figure2. a. The leg model consists of a shoulder, thigh, shank, and foot. All angles are measured in degrees with reference to vertical axes.
b. Three VDP oscillators are applied to hip, knee, ankle joints respectively, and coupled as a ring.

A four-link leg model will be investigated in order to implement the VDP oscillator. This leg introduces the basic features of a real human leg. The denotation of angles in the hip, knee, and ankle are shown in Figure2. Each joint is governed by a VDP oscillator, so one single leg consists of three oscillators.

Two basic connection methods can be considered for the oscillator network. The first method connects the oscillators as forward chain. This approach is a simple connection structure and will great simplify the system. However, it is limited in this research due to lack of enough dynamic properties to imitate human movement behaviors. Another method is to connect the oscillators as a ring with full connection (Figure 2). Such a network structure makes hip, knee, and ankle oscillators have inhibitory couplings with each other, and will exhibit some interesting properties.

Bar and Hemami (1987) had graphically presented the basic behaviors of the coupled VDP oscillator. However, the different coupling model and different application push this project to investigate the new parameter behaviors exhibited on a human-like robot leg. Although the coupling model is difficult to describe using analytical solution, a qualitative analysis can be derived by numerous simulations and trials.

Following numerous tedious simulations general effects of the parameters can be concluded.

u: Controls the degree of the nonlinearity of the oscillator, so it has an important effect on the shape of gait images. The ranges of the angle and angular velocity also vary with the parameter u.

p: Controls the amplitude of oscillator, and changes the oscillator frequency.

λ : The coupling coefficient, which represents the strength of oscillator's effect on each other. Its change will influence the phase and shape of gait image.

g: The frequency parameter of oscillator. Will significantly change the frequency of the gait image.

m: The offset parameter, which changes the angle and angular velocity range.

2. Real Human Gait

Before modeling a neural-oscillator based gait rhythm generator, experimental investigations of human gait is necessary. This paper only investigates the basic human walking gait as the first step to set up a biological inspired robot control system. Other movement behaviors, such as running, jumping can be generated through changing the oscillator parameters from the central pattern generator. The most direct method to collect the movement data is to observe the sequential photographs of the normal human movement. Winter (1990) published precise and detailed joint trajectory information of a regular man's walking gait. According to his data, the corresponding angle change figure and stick figure with respect to time are presented in Figure 3. The convention for joint angles is the same as Figure 2.

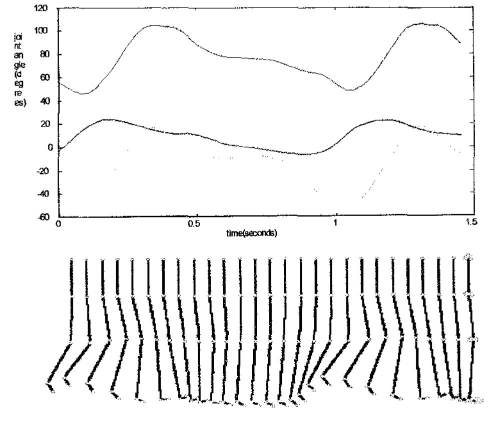

Figure3

a. The joint angle ranges of Hip, Knee, and Ankle for a regular man's walking gait.[Data from Winter (987)]

b. The stick figure of walking movement.

HIP	KNEE	ANKLE
$p^2 = 1$	$p^2 = 2$	$p^2 = 2$
$g^2 = 50$	$g^2 = 50$	$g^2 = 40$
$m = 40$	$m = 20$	$m = 12$
$u = 5$	$u = 5$	$u = 6$
$\lambda_{kh} = 0.2$	$\lambda_{hk} = 0.2$	$\lambda_{ka} = 0.2$
$\lambda_{ah} = -0.2$	$\lambda_{ak} = -0.2$	$\lambda_{ha} = -0.2$

Table 1. Final oscillator parameter values for a regular man's walking.

These data were taken from 106 frames with the interval about 0.014 seconds. It was easy to find from Figure 3 the joint angle ranges of a regular walking gait: the hip has a range from -7° to 25 °; the knee has a range from -55° to 20°; and the ankle joint has a range from 45° to 105°. At any given time, since the thigh begins its forward swing before the shank, the hip angle is always greater or equal to knee angle. Especially, there is a cross between hip angle and knee angle, in which results in a slight over swing on the knee joint. The reason for this phenomenon is the biological structure of the human leg joint is complex and flexible. For a rigid robot joint, this will not be allowed to appear in the movement for ensuring a stable control status.

3. Human Gait Simulation Using Neural Oscillators.

Due to the uncertainty of a coupled multi-oscillator system, it is impossible to analytically describe the oscillator behavior. Therefore, computer based numerical simulation is the only way to accurately solve for different coupling models. A stable parameter range of the VDP oscillator has been presented by Bar and Hemami (1987). Initial values of p, g, q, u, and λ can be selected based on their research results. Parameters are modified further according to the basic relationship between oscillator parameter and the stick figure gait image (see Figure 3). The oscillator simulation is programmed using Matlab/Simulink and solved numerically using the Fifth-Order Dormand-Prince method with an interval equal to 0.014s, which is the same step size as the measured gait. After numerous trials and comparisons, the final parameter values are given in Table 1. To meet the angle range of the real gait, the following scaling and offset have been applied to oscillator output.

$$q_h = 12X_h \quad q_k = 15X_k - 25 \quad q_a = 12X_a + 73 \qquad (4)$$

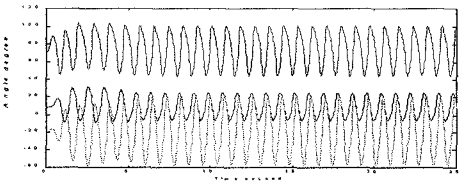

Figure4. Oscillator outputs in first 25 seconds. Outputs trend to constant amplitude and frequency after 5 seconds.

To numerically simulate the gait image, the initial conditions of the gait generator have been set to zero. Figure 4 shows the angle range of the hip, knee, and ankle generated by oscillators according to parameters of Table 1. By observing the numerical solutions, the data from 0-5 seconds (about 400-integration step sizes) are not periodic. This phenomenon is partially caused by the natural property of numerical algorithms, and also is affected by initial values. After 5 seconds, the oscillator outputs the constant amplitude and frequency values, which can be treated as the regular human gait. For an easy comparison with real gait image, Figure 5 one period of oscillation.

Clearly, the oscillator based gait rhythm generator can produce a similar gait motion as a real one. Not only the gait shape and amplitude, but also the gait frequency can be duplicated through tuning the oscillator parameters. The phase of the three joint angles is also reproduced as real one. Especially, there is a considerable reduction on angular velocity in the real gait image (follows the peak of the wave). The leg support phase results in this change. This is a very important property, because the period of the foot touching and leaving the ground plays a key role in the movement. The "stance phase" duration must be satisfied to ensure a stable body motion. It was thought that such regularity is difficult to solve without more additional oscillators (Zielińska 1995), Figure 5 reflects this property, in which the joint angular velocities have the obvious velocity reduction during support phase. Modifying shape coefficient u can make the wave shape close to real gait, but other parameters must be adjusted to overcome extra harmonics in transients, which caused a disturbance of gait rhythm.

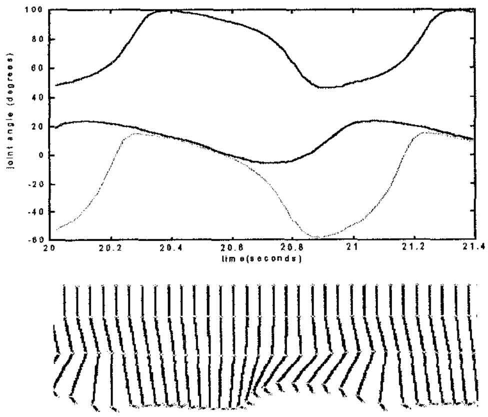

Figure5.
a. The joint angle ranges generated by oscillators using the parameters in Table 1.
b. The stick figure of walking gaits according to angle image.

Furthermore, unlike the real gait image, the knee angle in robot leg is never greater than the hip angle. This simplifies the mechanical structure and control of the robot leg.

III. CONTROL STRATEGY

As the part of biologically inspired walking machine control system, the coupled oscillator can generate the gait pattern similar to real human gait. To apply the trajectory to joints, a torque control compensator must be considered, whose input is desired trajectory from gait rhythm generator and output is the desired torque at the joint, as shown in Figure 1. There is a considerable range of literatures in the design of position or trajectory controllers for stationary manipulators. The proportional plus derivative (PD) and proportional plus integral plus derivative (PID) are the popular control laws for many industrial robots. Williamson (1999) utilized the coupled neural-oscillator (Matsuoka) as the rhythm generator of arm trajectories to simulate a variety of tasks such as sawing wood, throwing balls, and hammering nails. He used a low gain PD controller to get the desired torque output for robot arm joints. As is well known, the PD controller lacks of a global asymptotic stability proof due to the presence of gravitational effect (Kelly et al., 1996). The simple PD controller ignores the robot dynamics and usually is used for independent joint control, because it assumes that the coupling torque between the joints is small. Hence, the PD or PID controller can only represent adequate position control schemes for robot links. In order to obtain good trajectory tracking performance, a more sophisticated controller is necessary. The computed torque approach achieves tracking of the desired trajectories.

The dynamics of the robot should be derived prior to applying control laws into a robotic system. For a walking leg system, Newton-Euler formulation or Lagrangian formulation can be used for the derivation of the dynamic model of a robot leg. Generally, The EOM of a robot leg with n degrees of freedom in the joint space can be described by.

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = T \qquad (5)$$

where H(q) is the nxn inertia matrix; q is the nx1 joint variable vector; $C(q,\dot{q})\dot{q}$ is the nx1 vector of Coriolis and centrifugal force; G(q) is the nx1 vector of gravity loading; and T is the nx1 vector of the generalized forces applied at the joints. Wright (1999) has derived the EOM of the four-link, bottom-mounted leg using Newton-Euler method. Details and symbol meanings can be referred in that paper.

The computed torque controller has the theoretical performance advantage over the PD controller and will be implemented to simulate the dynamic system of robot leg. For a reference purpose, however, the PD controller will also be considered here. In the absence of disturbance and friction, the simple solution to the position control problem can be given by a PD controller.

$$\tau = Kv(\dot{q}_d - \dot{q}) + Kp(q_d - q) \qquad (6)$$

where Kv and Kp are nxn diagonal matrices of velocity and position gains. $\dot{q}_d, q_d$ are the desired joint angle and velocity respectively.

The computed torque control can be expressed according to following equations.

$$\tau = H(q)\theta^* + C(q,\dot{q})\dot{q}_d + G(q) \qquad (7)$$

where θ^* is given by

$$\theta^* = \ddot{q}_d + Kv(\dot{q}_d - \dot{q}) + Kp(q_d - q) \quad (8)$$

Similarly, Kv and Kp are nxn constant gain matrices, and $q_d, \dot{q}_d, \ddot{q}_d$ are desired angle, velocity, and acceleration respectively. This method was proposed by Spong and Vidyasagar (1989), in which the highly non-linear coupled dynamics of the robot leg are canceled and replaced by a simple decoupled linear second order system. If the robot model is exact, then the link of the robot is decoupled. To implement this control scheme, the inner-loop/outer-loop notion is used, in which inner-loop executes the complex non-linear control compensation ($\tau = H(q)\theta^* + C(q,\dot{q})\dot{q}_d + G(q)$), and the outer-loop computes the input in terms of inner loop ($\theta^* = \ddot{q}_d + Kv(\dot{q}_d - \dot{q}) + Kp(q_d - q)$). However, the major limitation of computed torque controller is, in practice, the dynamic model of the system cannot be known precisely, so the parametric uncertainty will result in an inexact cancellation of nonlinearities in the robot dynamics. To solve this problem, some analyses were performed by Baines and Mills (1998) based on research of Spong and Vidyasagar (1989).

Parameters	Thigh	Shank	foot
Length L(m)	0.32	0.40	0.25
Mass M(Kg)	5.7	2.65	0.83
Length of Center of mass (m)	0.14	0.17	0.13
Inertia about the center of mass(Kgm^2)	0.061	0.038	0.012

Table 2. Parameters of the leg model. All data from a regular human with Body Mass=57Kg and Body Height=1.65m.(Winter(1990)).

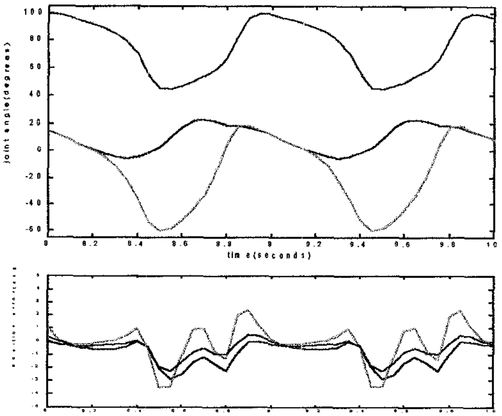

Figure6. a. The trajectory outputs of leg dynamics with the PD controller.There is a concavity in hip since PD controller can not decouple the leg dynamics completely.
b. Tracking error figure of joint angles. Solid : hip; Dashed: knee; Dashdot: ankle

IV. SIMULATION

Simulation models of the walking robot have proven valuable for testing hypotheses and verifying control laws based on experimental studies. Computer aided simulation is a process by which users can design and analyze systems without actually building hardware.

In this section, the computer simulation results of controlling the human-like robot leg are presented. The PD and computed torque controller are used to track the desired trajectories generated by the neural-oscillator. In the simulation study, ground force and disturbance are assumed to be unknown. Thus, the generalized external forces of EOM can be simplified to joint torque only. The parameters of the leg model are selected according anthropometry. Table2 lists the key parameters in terms of a regular man's leg (Winter 1990).

To test the performance of the controller, Trajectories generated by the gait rhythm generator are used, where the desired velocity and acceleration profiles are also derived from oscillators. The same computer platform and integral algorithm are used in controller simulation as in oscillator modeling. The PD controller gain matrix, in N.m.s/degree, is:

$$\begin{bmatrix} K_p \\ K_v \end{bmatrix} = \begin{bmatrix} 50 & 50 & 10 \\ 200 & 200 & 100 \end{bmatrix}$$

The simulation results of local PD joint controller with the leg dynamics are shown in Figure6. The EOM of the leg is derived from a four-link, bottom mounted robot leg, however, only three links --thigh, shank, and foot are controlled. The shoulder link is fixed in this simulation and will be controlled according body movement in the future. While the PD controller is adequate in most position controls, as is expected, it provides the least accurate tracking capability in this case. Especially, it suffers the disadvantages of overshoot, which makes the joint go beyond the specified position before actually stabilizing at it. This is also reflected in Figure 6, where the knee angle exceeds the hip angle and results in an abnormal position at the knee joint. Furthermore, There is an obvious concavity in the hip angle close to the peak of the knee angle since PD controller can not decouple the leg dynamics completely.

Figure 7 provides the trajectory traces of the gait rhythm generator using computed torque controller with same gain matrix with PD controller. As figure 6, consider the outputs from 8s-10s for a stable and clear gait outputs. The figure shows a significant reduction in tracking errors for three joints compared with the PD controller. Specifically, the tracking errors (peak to peak) are reduced about from 7°to less than 1°. Again, the concavity on the hip joint is gone and the curve gets smooth in this case. The simulation results of computed torque controller shows the theoretical performance advantage over the PD controller.

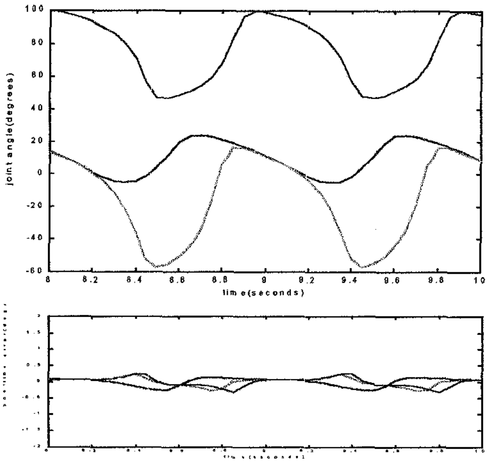

Figure7. a. The trajectory outputs of leg dynamics with the Computed torque controller.
b. Tracking error figure of joint.
Solid : hip; Dashed: knee; Dashdot: ankle

V. CONCLUSION

In this paper, a coupled neural-oscillator based gait rhythm generator was proposed to produce a similar gait motion as real man. A set of parameters was derived, which can duplicate a man's walking gait with same shape, amplitude and frequency. Especially, the support phase of human walking, which is very important transition in human locomotion, is also reproduced by adding the ankle coupling in the oscillator network. Two torque controllers have been investigated based on a four-link, human-like robot leg model using the trajectories generated by oscillators. The computed torque controller shows superior performance over the popular PD controller according to the simulation results.

Further works will be expanded into running and jumping investigation with gait transitions. A physical robot leg will be manufactured to transfer the software simulation into hardware-in-the-loop prototype testing.

REFERENCE

Baines, P. J., J. K. Mills (1998) Feedback linearized joint torque control of a geared, DC motor driven industrial robot. *International Journal of Robotics Research.* 17, pp169-192.

Bay, J. S., H. Hemami. (1987). Modeling of a neural pattern generator with coupled nonlinear oscillators. *IEEE Transactions on Biomedical Engineering.* Vol. 34, pp297-306.

Berns, K., W. Ilg, M. Deck, J. Albiez, R. Dillmann. (1999). Mechanical construction and computer architecture of the four-legged walking machine BISAM. *IEEE/ASME Transactions on Mechatronics.* Vol. 4, pp30-38.

Brown, T. G. (1914). On the nature of the fundamental activity of the nervous centers. *Journal Physiology.*

Collins, J. J., S. A. Richmond. (1994). Hard-wired central pattern generators for quadrupedal locomotion. *Biological Cybernetics.* 71, 375-385.

Kelly, R., R. Carelli (1996). A class of nonlinear PD-type controllers for robot manipulators. *Journal of Robotics System.* 13, pp793-802.

Pribe, C., S. Grossberg, M. A. Cohen (1997). Neural control of interlimb oscillations. *Biological Cybernetics.* 77, pp141-152.

Spong, M. W., M. Vidyasagar(1989). *Robot Dynamics and Control.* John Wiley & Sons. New York.

Wadden, T, O. Ekeberg. (1998) A neuro-mechanical model pf legged locomotion: single leg control. *Biological Cybernetics.* 79, pp161-173.

Williamson, M. M.(1999) Robot arm control exploiting natural dynamics. *Doctoral Dissertation*. MIT. Cambridge, Massachusetts.

Winter, D. A.(1990) *Biomechanics and Motor Control of Human Movement.* John Wiley & Sons. New York.

Wright, A. B. (1999) Derivation of equations of motion for a four-link robotic leg for walking vehicle. *Journal of Arkansas Academy of Science.* Vol.53, pp137-142. (http://theduchy.ualr.edu/papers/aas1.pdf)

Zielińska, T.(1996) Coupled oscillators utilised as gait rhythm generators of a two-legged walking machine.. *Biological Cybernetics.* 74, pp256-273.