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BIOLOGICALLY INSPIRED QUADRUPED ROBOT BIOSBOT: MODELING, SIMULATION AND EXPERIMENT

Xu Guan, Haojun Zheng, Xiuli Zhang
Department of Precision Instruments and Mechanology, School of Mechanical Engineering
Tsinghua University, Beijing, 100084, P.R.China
guanx02@mails.tsinghua.edu.cn

Abstract

A biocybernetics-based control scheme for the walking robot BIOSBOT (a quadruped robot system) is presented. The ADAMS (Automatic Dynamic Analysis of Mechanical Systems) computer program is used to model and simulate the performance of BIOSBOT based on CPG (central pattern generator) control theory. Reflexes are also introduced to increase the reactivity between BIOSBOT and the environments. A new method for gait transition is investigated. Dynamic simulations which combine a CPG control algorithm created by MATLAB Simulink Toolkit have been carried out. The success in realization of four typical quadrupedal robotic bio-gaits, gait transform during walking and dynamic walking on irregular terrains shows that the biologically inspired control has ability for autonomous adaptation to unknown irregular terrain. MPEG footage of real experiments on real robot can be seen at: http://thsr.pim.tsinghua.edu.cn.

Keywords: Modeling, simulation, CPG, quadruped robot.

1 Introduction

In the past few decades, the development of walking or running machine has drawn significant attention in the field of robotics. Many previous studies of legged robots have been performed. About dynamic walking on regular terrain, monopod [1] biped [2, 3] and quadruped [4, 5 and 6] robots have been studied. Most of these earlier studies employed precise models of a robot and an environment and also involved planning foot trajectories as well as controlling joint motions on the basis of an analysis of the models. The robotic gaits, which are generated by this traditional model-based approach, are rigid and inflexible, and lack the abilities of self-organization, especially when a legged robot moves quickly in a variety of places or walking on irregular terrain. On the other hand, animals' walking, which is mainly generated by a combination of a rhythm pattern generator (CPG: Central Pattern Generator) and reflexes, shows marvelous abilities in autonomous adaptation. Transfer of biological principles into the construction of quadruped walking machines has been studied [7]. About adaptive dynamic walking of a quadruped robot on irregular terrain with a high degree of irregularity by using a CPG and a reflex mechanism has been studied [8, 9, 10].

In our previous research, CPG-based method for motion control of robot [11] and bio-reflex-based robot adaptive motion controlling theory [12] have been studied. The biologically-inspired dynamic walking controller of a quadruped robot has been realized [13]. For in-depth study of quadrupedal robot, we use the ADAMS (Automatic Dynamic Analysis of Mechanical Systems) computer program to create a parameterized physical model of our robot, add a CPG control algorithm created by MATLAB and simulate the performance of the quadruped robot system based on CPG control theory. A new method for gait transition is investigated. The simulation results demonstrate the realization of typical quadrupedal robotic bio-gaits, gait transform during walking and walking on irregular terrains. These are also proved by our real experiments.

2 The Biocybernetics-based Control Approach

Unlike traditional model-based approach and behavior-based approach, biocybernetics-based approach is a kind of new simple and natural motion-controlling method formed by modeling, simplifying and improving some biocybernetic models or mechanisms, such as animal's rhythmic-motion-control area of central pattern generator, higher control and regulation center, reflex system, etc [14].

A core theory of biological motion control, CPG theory, is used to research the generation of typical gaits of the quadruped. As a model of CPG, we use a neural oscillator (Figure 1) proposed by Matsuoka [15] and apply to the quadruped robot BIOSBOT. Each neuron is represented by the non-linear differential equations. A neural oscillator (N.O.) consists of two mutually inhibiting neurons, which produce multiple or single periodic signals with steady phase-lock relation to control the rhythmic motion of limbs or other parts. CPG neural circuit can be looked as a distributed system consisting of a group of neural oscillators coupled each other, which generates phase-lock rhythmic signals.

Based on biological central pattern generator, the relationship between weight matrix of CPG net and bio-gait is elucidated; the method to produce four typical quadrupedal gaits by using different weight matrixes is presented in [14].

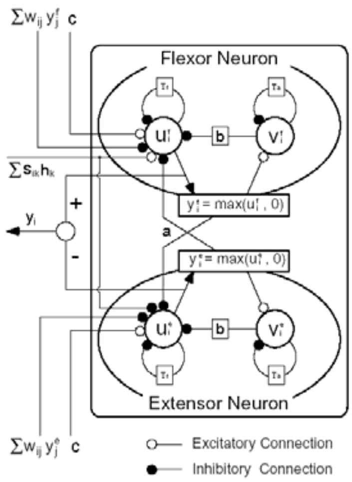


Figure 1: Model of neural oscillator

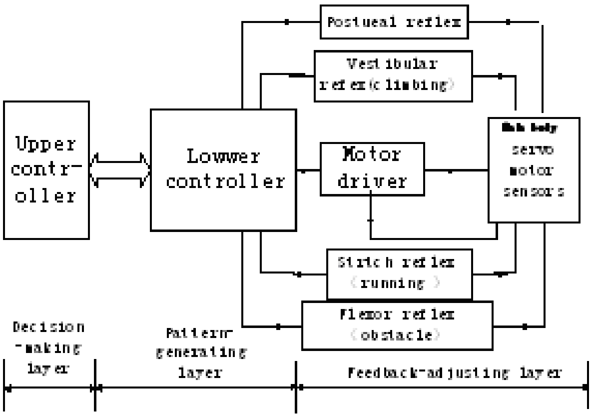


Figure 2: The overall biocybernetics-based control scheme

An overall biocybernetics-based control scheme of the quadruped control system, as showed in Figure 2, which includes three function layers (decision making layer, pattern generating layer and feedback adjustment layer) for implement biocybernetics-based approach, has been carried out. The decision making layer simulates the higher nerve centre, adjusts and controls the motion of the robot; The pattern generating layer, which consists of neural oscillation units, is used to generate phase-lock rhythmic signals to drive the motors in the robot; The feedback adjustment layer makes feedback network model based on the animals' reflex mechanism, so as to improve the robot's ability for autonomous adaptation to unknown irregular terrain.

3 Robot Model

In the BIOSBOT project we developed a biocybernetics-based quadrupedal walking robot (see Figure 3). The robot is 400mm in length, 320mm in width and 350mm in height when it's stand-up. The weight of the fully equipped robots (including 8 DC servo-motors, 8 photoelectric encoders, sensors such as inclinometer, limit switch and touch switch) is 5.7 kg. Twelve DOFs (Degree Of Freedom) distribute in four legs averagely; each leg of the robot provides 3 degrees of freedom (including a hip rotational DOF, a knee rotational DOF and a passive rotational DOF which acts as an ankle) which we feel confident is the minimum needed in a flexible quadrupedal walking robot.

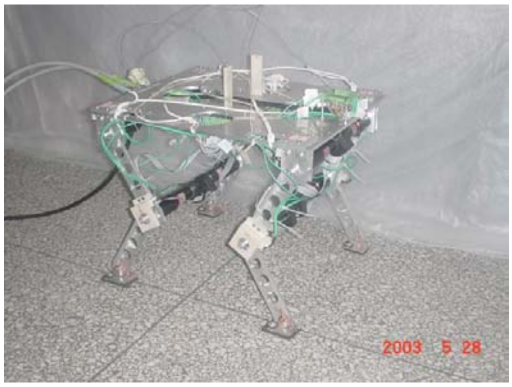


Figure 3: Structure of quadruped prototype

Since our motion control approach is also suitable for the more widely studies of quadrupedal robot, we build up a quadrupedal robot virtual prototype by using ADAMS, the kinematic and dynamic simulation software. The mechanical model of the robot BIOSBOT consists of 25 parts which are coupled by 24 joints (rotational and fixed ones): one scalable body part and four homogenous legs. Each leg consists of a short link firmly attached to the body which houses the thoracic joint. The "thigh" is connected to the short link with the hip joint. "Thigh" and "shank" are connected by the knee joint. A passive rotational joint serves as ankle between "foot" and "shank". Therefore each leg is movable with three active joints. The modeling is based on the assumptions:

1. active joints are flexible.
2. all parts are rigid.

Robot construction requires frequent design changes; therefore a parametric robot model is well suited for design optimization and virtual motion experiments. We have created about 50 design variables which allow instant parameter modification of each part: density, mass, inertia and geometrical shape of each part, initial position and orientation conditions of each leg, individual rotational scope of each joint, and also some characters of contact force between the robot and the terrains, such as stiffness, friction coefficient and transition velocity of static friction. For example, in the nature, quadruped walking animals have various joint configurations, such as all-elbow, all-knee, fore-elbow and back-knee, fore-knee and back-elbow. This variety can also be displayed on our parameterized model (Figure 4).

The entire geometrical information is contained in the skeleton of the model in parameterized form: design points for the position and tripod markers for the orientation of parts. Each part is connected to at least one design point or one marker. The design points and tripod markers are chained; changing one of them affects the entire configuration. Thus the entire model is adapted automatically when one parameter is modified. This method is very effective for parameterized research of a mechanical model, especially for the model with control system which is introduced by using a Matlab Simulink model for implementing complicated description of control.

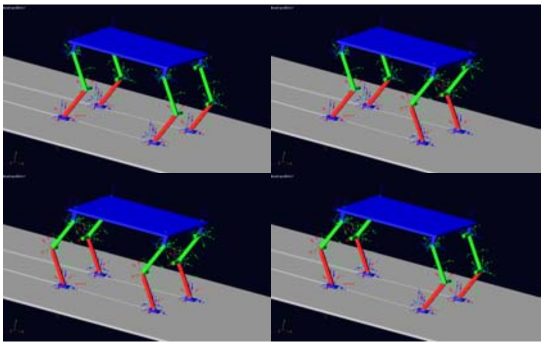


Figure 4: One model, four different designs in joint configuration.

4 Robotic Control System

We use the Controls Toolkit, which comes embedded in ADAMS/View, together with control system design packages such as MATLAB here, to build CPG-based controllers into our mechanical models.

In the ADAMS model of robot, we define the inputs and outputs, through which we can connect the ADAMS model with the CPG control model. The inputs describe the variables that come into ADAMS and the outputs describe the variables that go back to the controls application. Thus, a closed loop between ADAMS and the MATLAB is composed. The complete ADAMS/MATLAB robot control system is shown in Figure 5. The block adams_sub in Figure.5 is the dynamic model the robot, which includes information of the robot such as part masses, inertias and geometrical shapes, joint rotational scopes, and also some feathers of forces. We control the robot by defining the motion of eight joints (four hip joints and four knee joints) on robot. The function of the motion of the four hip joints is calculated by CPG model through which we can modify the gait of the robot and control the locomotion of the robot under complicated condition of terrain. The function of the motion of the four knee joints is derived from the control signals of the hip joint in the same leg as follows:

$$\theta_k = \cos(\mathrm{sgn}(\frac{d\theta_h}{dt})\times(\theta_h - A_h)\times\pi/2+\varphi) \qquad (1)$$

where θ_k and θ_h is the position of the knee joint and the hip joint, respectively. A_h is the swing amplitude of the hip joint. Φ is the phase between motion of the hip joint and the knee joint.

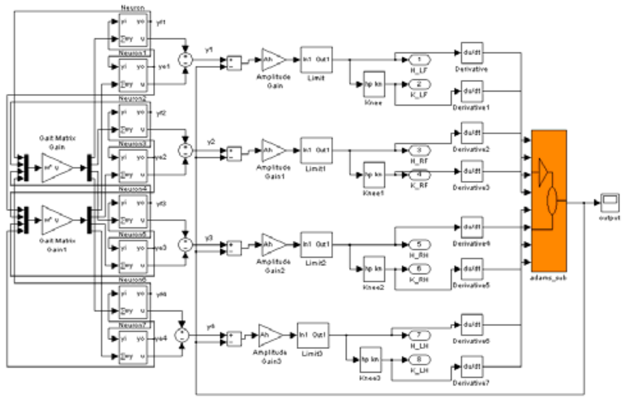


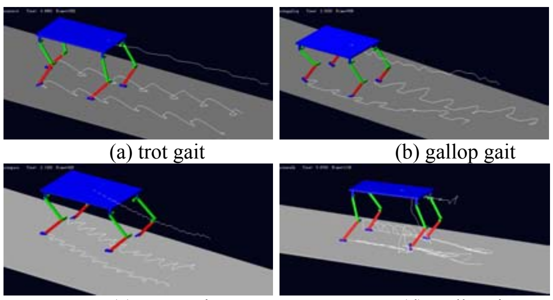
Figure 5: ADAMS/MATLAB robot control system

5 Simulation Results

The objective of our simulations is to demonstrate the ability of the quadrupedal robot with biologically inspired control to realize i) four typical quadrupedal robotic bio-gaits; ii) gait transform during walking; iii) walking on irregular terrains such as slope and obstacle.

5.1 Four Typical Quadrupedal Robotic Bio-gaits

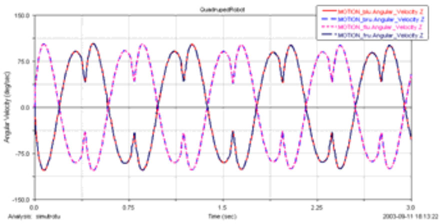
'Gait' means a pattern of discrete foot placements performed in a given sequence. By using different weight matrixes in CPG network, four typical quadrupedal gaits are obtained. Simulation results of four typical quadrupedal robotic bio-gaits (trot, gallop, pace, walk) are shown in Figure 6 and Figure 7. Figure 6 shows the traces of the centroid and the foot of the robot when walking with different gaits. Figure 7 shows the motions of the four hip joints when robot is walking with different gaits. The difference of the phase relationship between different gaits can be seen from the simulation results.



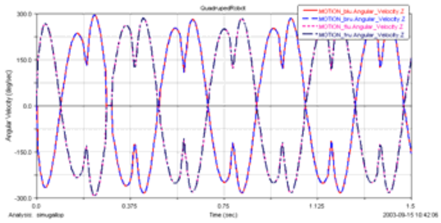
(a) trot gait (b) gallop gait

(c) pace gait (d) walk gait

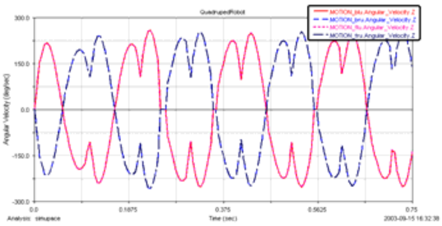
Figure 6: Traces of the centroid of the body and the foot.



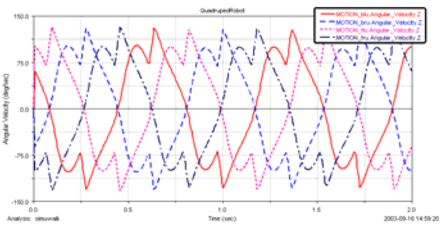
(a) trot



(b) gallop



(c) pace



(d) walk

Figure 7: The angle velocity of the hip joints of different gaits.

5.2 Gait Transition during Walking

In nature, quadruped walking animals such as horses or cats change their gait to be suited to their walking speed. This is very important to realize smooth walking and smooth running. Within one gait pattern, the stride can be shifted while walking speed changes continuously. When shifting from one gait pattern to another, however, it is not always an easy task to maintain a continuous change of velocity. Many methods of the gait transition for the quadruped walking robot have been proposed [16, 17, 18, 19, and 20]. However, these methods are complicated and not easy to be implemented.

For realize smooth gait transition during walking, we define a subsection function, in which we define sine and cosine as the transition function between two gaits. The swing amplitude of the transition function is very equal to the swing of the value of vibration generated by CPG. In this simulation, from start to 3.95s, the robot walks with trot gait; from 3.95s to 4.75s, the robot walks with transition gait; from 4.75s to 8.0s, the robot walks with gallop gait. The transition point is smooth which can be seen from the simulation results (Figure 8). In this simulation the swing amplitude generated by CPG is equal with trot and gallop gait. The transition function can also be adjusted to adapt different swing amplitude of different gait. By using this method of defining simple transition function, smooth gait transition between any of the four typical quadrupedal gaits can be realized.

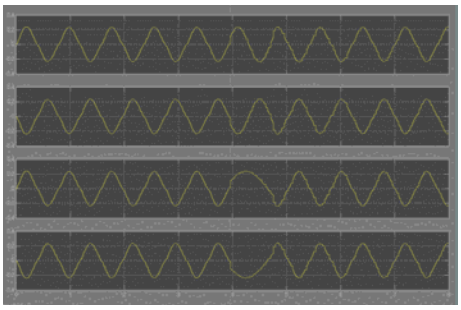


Figure 8: The motion of the four hip joints during gait transition

5.3 Walking on Irregular Terrains

Reflexes between the robot and the environments have been introduced to realize dynamic walking on irregular terrains. Figure 9 and Figure 10 show simulation results of the robot walking on a 10 degree slope. We can see from the simulation results that the velocity of the robot is about 0.625m/s and the fluctuation of the centroid of the body is about 5.13%. Figure 11 and Figure 12 show simulation results of the robot walking over an obstacle and three obstacles each of which has a height of 20mm. In Figure 13 the distance between the second obstacle and the third obstacle is less than the length of the robot. From these simulation results we see the biocybernetics-based control based on CPG and reflex is effective for robot to walk on irregular terrains and this is also proved by our real experiments (Figure 13)

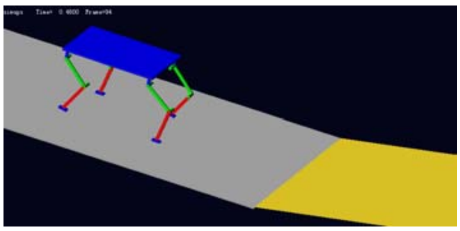
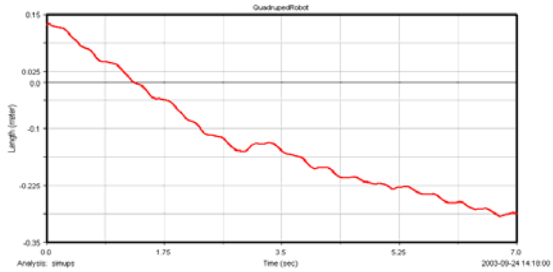
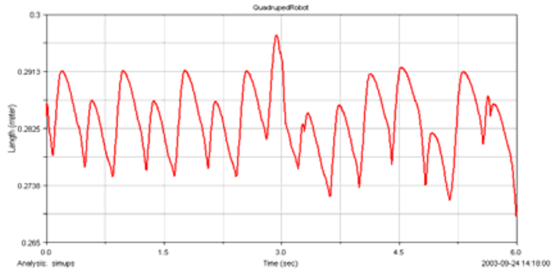


Figure 9: Walk on a 10 degree slope



(a) The trajectory the centroid of the body



(b) The fluctuation of the centroid of the body

Figure 10: The motion of the centroid of the body

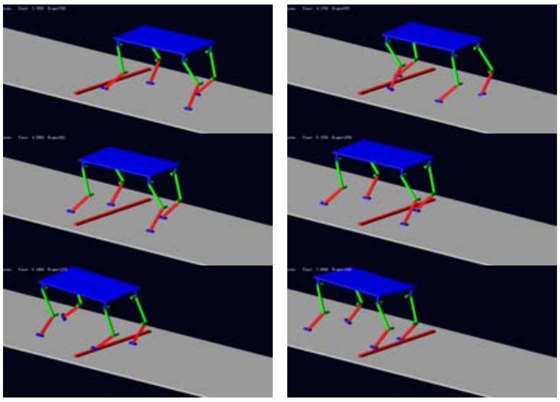
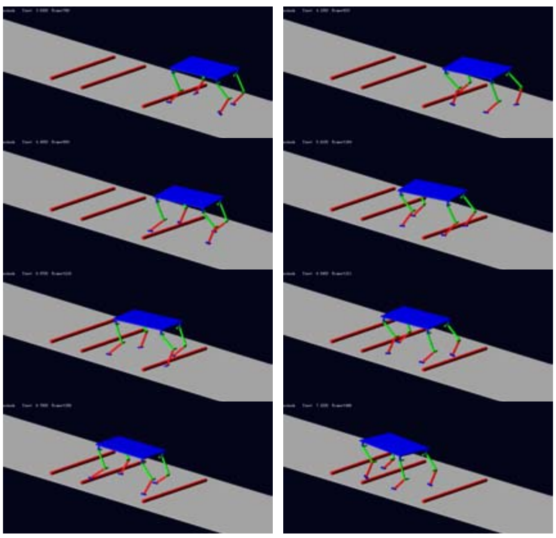


Figure 11: Walk over a 20mm height obstacle



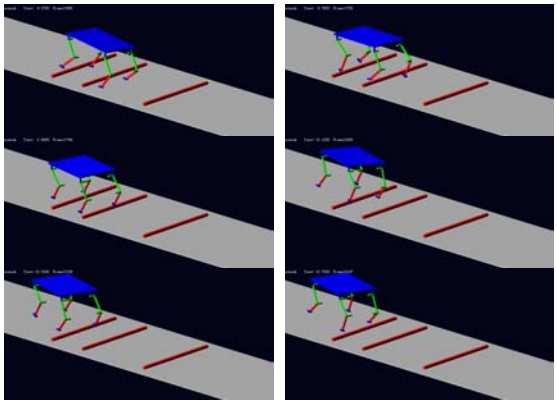
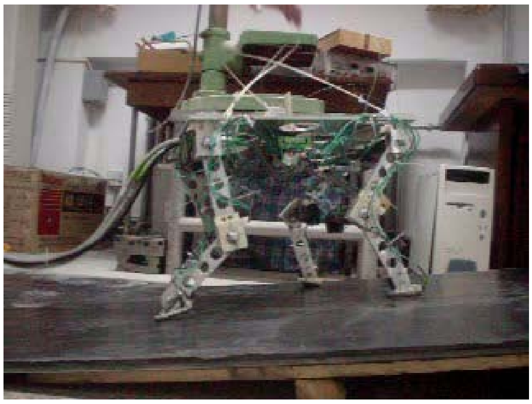
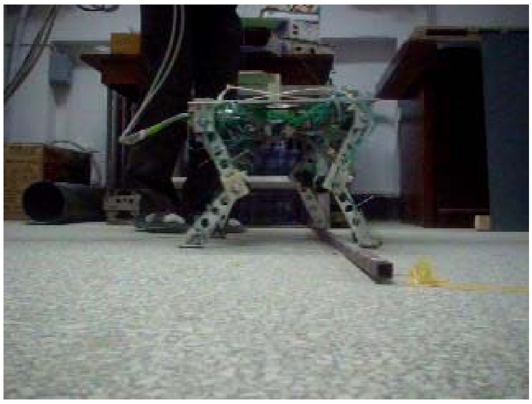


Figure 12: Walk over three 20mm height obstacles



(a) Walk on a 10 degree slope



(b) Walk over a 20mm height obstacle

Figure 13: Walk on irregular terrains

6 Conclusions and Outlook

We have created a parameterized physical model for the quadrupedal robot and added CPG controllers into our robot model. Proved by computer simulation, robotic bio-gait can be generated by using the CPG mathematic model and a stable and coordinated motion is got. We also proposed a new method for gait transition of the quadrupedal walking robot. The simulation results represented here also demonstrate that the biocybernetic control method based on CPG and reflex is effective for robot walking on irregular terrains.

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