Biologically-inspired Adaptive Movement Control for a Quadrupedal Robot

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ABSTRACT

Biologically-inspired robot motion control has attracted a lot of interests because of its potential to make a robot perform better and the value of such study to understand animals' behaviors. This paper presented a quadrupedal robot, Biosbot, with variety of motion abilities and adaptability to its environment. We employed biological neural mechanisms, such as central pattern generator, flexor reflex and postural reflex as Biosbot's control system, meanwhile designed its acts after its animal counterpart, a cat. Biosbot can walk in different gaits, transfer from one gait to another, turn, clear obstacles and walk up and down hill autonomously, to adapt to its environment. The successful walking experiments with Biosbot prove the approach and control model has the ability to improve legged robot's performances.

Keywords: quadrupedal robot, rhythmic motion, central pattern generator (CPG), biological reflex

1. INTRODUCTION

Adaptive movement control for a legged robot has long been a challenge for roboticists because of the redundant DOFs of the robot and difficulty in modeling an unpredictable environment. Driven by the dissatisfaction with the performance of robots controlled by classical dynamics, a number of people somewhat independently began around 1990 rethinking the control of legged robot by introducing biologically-inspired neural control mechanisms. Kimura realized a quadrupedal robot dynamic walking on slopes, clearing obstacles, walking on steps and running, by employing various biological reflexes and designing an elaborate robot [1, 2]. Taga presented a model of the neuro-musculo-skeletal system for human locomotion [3]. The biped robot is robust to perturbations and can walk up inclines, and avoids obstacles [4]. Fujii explored quadrupedal robot walking on both flat terrain and slopes by imitating a neuromodulatory mechanism [5]. Tsujita designed a control system consisting of pattern controller and leg controller, which controls a quadrupedal robot walking in different gaits [6, 7].

Biological control mechanisms have the potential to make the legged robot perform in a better way. In this field, there are more to explore. This paper presented a biological concepts based quadrupedal robot, which can walk rhythmic movements in different gaits, transit from one gait to another smoothly, turn without yaw joints, walk up and down hill and clear obstacles in unknown environment.

2. QUADRUPEDAL ROBOT

We constructed a quadrupedal robot, Biosbot - Biologically Inspired Robot. Each leg of the robot has three joints: hip, knee and ankle, with one pitching DOF. Hips and knees are active joints driven by DC motors. Ankles are spring damper passive joints. All joints can rotate up to 180°. The robot is equipped with these sensors: a photo encoder on each joint, contact switches on the toe of each leg to detect obstacles, pitch and roll inclinometers on the trunk to acquire inclination of the terrain and sense the smoothness of the performance. The robot has dimensions of 400mm×320mm×300mm, and a mass of 5.7kg, as shown in Figure 1.

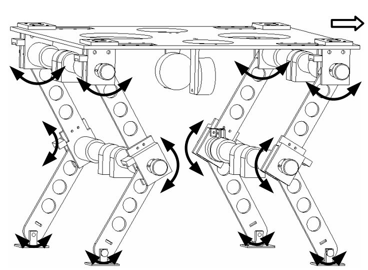


Figure 1 Quadrupedal robot Biosbot

The environment Biosbot walks in, as shown in Figure 2, has a flat, a long bar with cross section of 20mm×20mm as an obstacle and a continuously changing slope with a maximum pitch angle up to around 12°. The profile parameters of the terrain are unknown to the robot in advance.

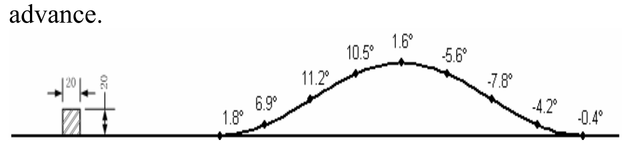


Figure 2 Experiment terrain

3. RHYTHMIC MOVEMENT MODEL

It is believed that animals' rhythmic motion is controlled by CPGs, networks of neurons in vertebrate spinal cords and invertebrate thoracic ganglia, capable of generating rhythmic muscular activity in the absence of sensory feedback. We use a CPG model, proposed by Matsuoka [8, 9], to control the quadrupedal robot. Matsuoka's oscillator consists of two reciprocally inhibited neurons, which correspond to the flexor neuron and extensor neuron in animals respectively. For the quadrupedal robot, we build a fully-connected CPG network using four Matsuoka's oscillators connected one another (Figure 3), which is represented in vector equation set in Eq.(1).

$$\begin{cases} T_r \dot{\mathbf{U}}^{f,e} + \mathbf{U}^{f,e} = b\mathbf{V}^{f,e} + a\mathbf{Y}^{e,f} + \mathbf{W}\cdot\mathbf{Y}^{f,e} + \mathbf{S}\cdot\mathbf{G}^{f,e} + c\mathbf{E}, \\ T_a \dot{\mathbf{V}}^{f,e} + \mathbf{V}^{f,e} = \mathbf{Y}^{f,e}, \\ y_i^{f,e} = \max(u_i^{f,e}, 0), \\ \mathbf{Y} = p(\mathbf{U}^f - \mathbf{U}^e). \\ \mathbf{U}^{f,e}, \mathbf{V}^{f,e}, \mathbf{Y}^{f,e}, \mathbf{Y} \in R^n, \mathbf{W} \in R^{n\times n}, \mathbf{S} \in R^{n\times m}, \mathbf{G} \in R^m, \\ \mathbf{E} = [\underbrace{1, 1, \cdots, 1}_{n}]^T,\ i = 1, 2, \cdots, n. \end{cases} \tag{1}$$

where the sub- and super-scripts and the variables

- i, n, m, f and e denotes the i-th oscillator, number of oscillators, number of sensing inputs, flexor neuron and extensor neuron respectively,
- $\mathbf{U}$ are the neuronal states,
- $\mathbf{V}$ and b is internal adaptability and an adaptive coefficient respectively,
- T_r is a rising time constant which determines the oscillation period,
- T_a is an adaptability time constant which characterizes the delay of the adaptability effect,
- c is constant tonic input from higher levels which linearly determines the output amplitude,
- p functions as a regulating gain that makes the output amplitude equal c,
- $\mathbf{Y}^{f,e}$ and a is the neuronal outputs and an inhibition coefficient of the neuron-neuron coupling term respectively,
- $\mathbf{W}$ is a gait matrix of the oscillator-oscillator coupling term, which represents the walking pattern of a legged robot,
- $\mathbf{S}$ and $\mathbf{G}$ are sensing inputs and reflex gains of the feedback term respectively,
- $\mathbf{Y}$ are a set of stably-oscillating outputs of the CPG, which are used as angular position control signals for the quadrupedal robot.

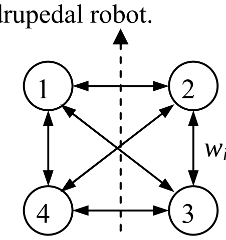


Figure 3 A fully-connected CPG network for the quadrupedal robot. Oscillators 1-4 correspond to the left front, right front, right hind and left hind legs respectively. Dashed arrow points to the head.

4. GAIT TRANSITION

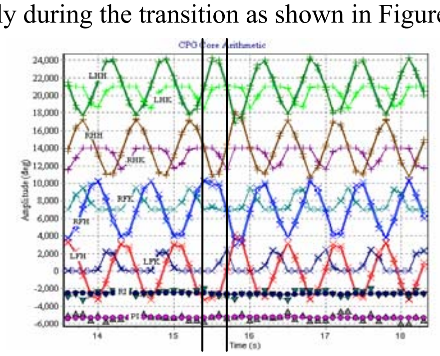
The fully-connected CPG network in Figure 3, composed of all identical oscillators and having connections between any two oscillators, endows each leg with equal qualities, and can express all kinds of phase relationship between legs, so as to make the robot walking in various gaits. Quadruped has four typical gaits: walk, trot, pace and bound. We represented the gait matrix of the CPG network, $\mathbf{W}(w_{ij})_{n\times n}$ as follows, with its elements of 0, -1 and +1 indicating the connected two legs' phase relations.

$$\mathbf{W}_{wk} = \begin{bmatrix} 0 & -1 & -1 & -1 \\ -1 & 0 & -1 & -1 \\ -1 & -1 & 0 & -1 \\ -1 & -1 & -1 & 0 \end{bmatrix} \mathbf{W}_{tt} = \begin{bmatrix} 0 & -1 & 1 & -1 \\ -1 & 0 & -1 & 1 \\ 1 & -1 & 0 & -1 \\ -1 & 1 & -1 & 0 \end{bmatrix}$$

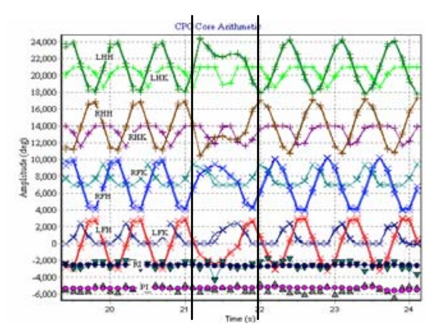
$$\mathbf{W}_{pc} = \begin{bmatrix} 0 & -1 & -1 & 1 \\ -1 & 0 & 1 & -1 \\ -1 & 1 & 0 & -1 \\ 1 & -1 & -1 & 0 \end{bmatrix} \mathbf{W}_{bd} = \begin{bmatrix} 0 & 1 & -1 & -1 \\ 1 & 0 & -1 & -1 \\ -1 & -1 & 0 & 1 \\ -1 & -1 & 1 & 0 \end{bmatrix} \tag{2}$$

Using different W for the CPG model, the quadrupedal can walk in different gait.

We realized gait transitions by directly replacing the gait matrix in CPG model [10]. Figure 4 shows the actual joints trajectories of the gait transitions from walk to trot and from trot to walk. The two vertical lines mark the transition period. The transition can be completed within one or two walking cycles, and the robot moves smoothly during the transition as shown in Figure 5.



a) walk-trot



b) trot-walk

Figure 4 Actual joints trajectories of gait transitions. The y-axis is in arbitrary units, because the data have been normalized in order to display all curves separately and distinctly. The relative phases and amplitudes of the

curves are unaffected by the normalization.
The labels are: LFH - left front hip; RFH - right front hip; RHH – right hind hip; LHH - left hind hip; LFK - left front knee; RFK - right front knee; RHK – right hind knee; LHK - left hind knee.

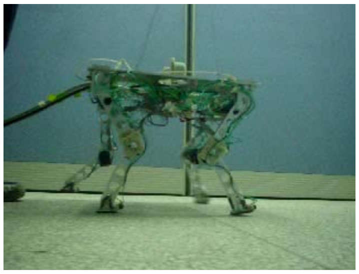


Figure 5 Biosbot transiting gaits

5. VARIOUS MOTIONS CONTROLED WITH CPG

5.1 Turn

Biosbot has no yaw joints. We realized the turn for it by changing the length of its left and right legs and setting different swing amplitudes for them, so that the distances its left legs and right legs move will differ to make it turn. If we want it to turn left, make the left legs shorter and swing less than right legs, as shown in Figure 6. Which, however, can cause the robot slipping, and it is difficult to make a turn with an exact degree without a directional sensor.

Figure 6 Biosbot turning left

5.2 Clearing obstacle

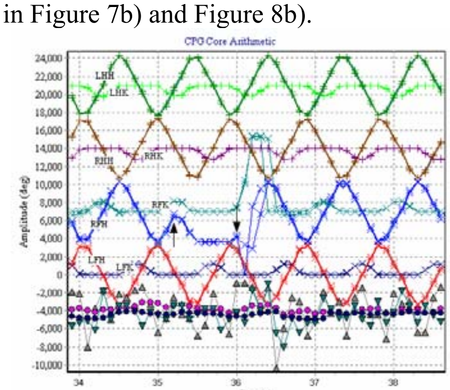
Animals use flexor reflex to escape or clear an obstacle when their limb bumping it. We employed the biological flexor reflex to make the quadrupedal robot clear obstacles in its environment autonomously. We modeled the flexor reflex by imitating a cat's clearing-obstacle behavior. It has been found, the cat retracts back its leg, then lifts up higher to clear an obstacle when bumping it during anterior swing (AS); while the leg retracts back and touches down on the ground when bumping the obstacle during posterior swing (PS).
To step over an obstacle, the cat flexes its leg like a scissor much more than normal, to get a higher foot clearance.

A. Bumping during AS

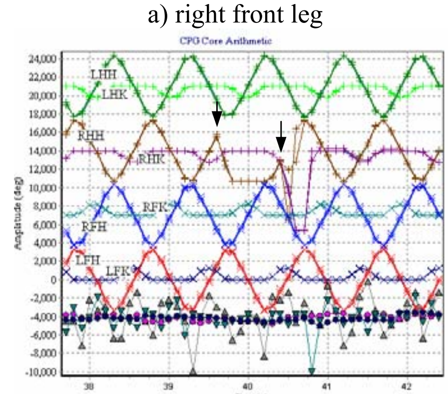
The flexor reflex acts during AS are designed only for the bumping leg as three act series namely, AS-pattern:
1) Retracting back: the hip output decreases linearly to make the leg retract back, while the knee output increases for elbow-style joint or decreases for knee-style joint, to ensure the hip and the knee flex like a scissor to lift up the foot.
2) Stepping over: the hip output increases linearly to make the leg swing forward, while the knee keeps unmoving, to step over the obstacle.
3) Touching down: the hip keeps swinging and the knee returns back to its normal swing-to-stance phase-switch position.

B. Bumping during PS

The flexor reflex acts during PS are designed as follows. The hip of the bumping leg decreases linearly to the normal stance-to-swing phase-switch point during the reflex time, then keeps unmoving until the beginning of next swing, namely, PS-pattern. The knee doesn't reflex.
A long bar with cross section of 20mm×20mm, was placed in the experimental environment as an obstacle. The location of the bar is unknown to the robot, so that the swinging leg can bump on it at any phase location. We controlled Biosbot by combining the flexor reflex with its basic rhythmic locomotion produced by the CPG. As shown in Figure 7a), Biosbot executes proper flexor reflex when its right front leg (Leg RF) bumps the bar under two different situations. At t = 35.2s, Leg RF bumps the obstacle during PS, a PS-pattern is triggered. With its hip output decreasing and its knee output unchanged, Leg RF retracts back and touches down on the ground. At t = 36.0s, Leg RF bumps the obstacle again but during AS, an AS-pattern is triggered. With its hip output decreasing and its knee output increasing, Leg RF retracts back and lifts up its foot to step over the obstacle (Figure 8a). Similar flexor reflex and clearing obstacle on right hind leg under the two situations are shown in Figure 7b) and Figure 8b).



a) right front leg



b) right hind leg

Figure 7 Actual reflex output curves of Biosbot clearing an obstacle

a) right front leg

b) right hind leg

Figure 8 Videos of Biosbot clearing an obstacle

From Figure 8, we can see the foot clearance of the bumping leg is much higher than the bar. That implies the robot can clear a bar higher than 20mm, whereas control experiments with no flexor reflex employed show the robot fails to clear an obstacle 20mm high.

5.3 Walking up and down hill

Walking up and down hill requires animals dealing with possible slipping or falling down caused by the offset of center of gravity (COG) of their body. Animal's walking on slope benefits from its postural reflex, which adjusts the animal's posture by changing its legs' movement depending on body's postural information sensed by vestibular organ in inner ear and other proprioceptors. We adjust the quadrupedal robot's posture by changing its leg extensions, i.e. the leg motion ranges. It is realized by modifying the mid-position of the hips and the knees, as shown in
Figure **9**.

To adapt to a slope with changing inclination, the value of the hips' mid-position increment is acquired dependently on the inclination of the slope, using a pitch inclinometer attached to the robot's trunk. We introduced the pitch angle of the slope, α, to S·G in the CPG model as a linear function. That will change the hips' mid-position automatically as the CPG outputs vary with the slope inclination.

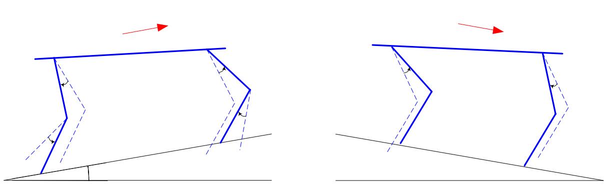
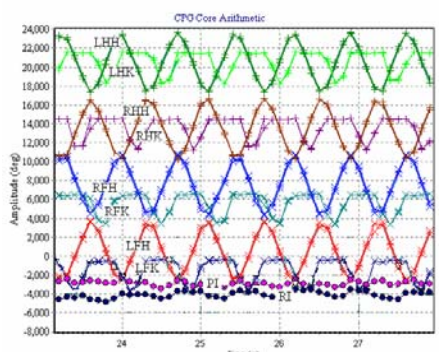


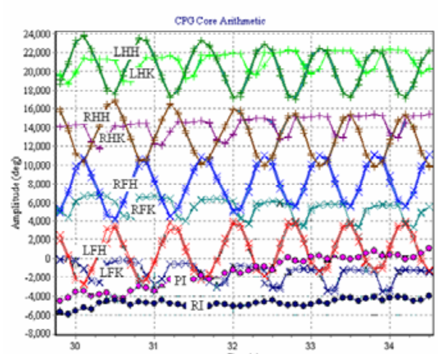
Figure 9 Postural adjustment of the quadrupedal robot when walking up and down hill. The dotted lines are the pre-adjusted positions. α is the pitch angle of the slope. Δθ is legs' mid-position change.

We controlled Biosbot by combining the postural reflex with the CPG. Biosbot walks around in an environment that includes flat terrain and a man-made slope. When Biosbot walks on the flat, the controllers exhibit normal outputs curves (Figure 10a) and Biosbot's trunk is horizontal (Figure 11a). When walking uphill, depending on the pitch angles of the slope, the output curves of the two front hips move gradually upward, that is, their mid-positions increase continuously, and the output curves of the two front knees move correspondingly downward. At the same time, the output curves of the two hind hips move downward with their mid-positions decreasing, and the output curves of the two hind knees move upward (Figure 10b). Thereby, Biosbot obtains a posture in which the head is lower than the tail, to keep its balance and counteract slipping (Figure 11b). When walking downhill, the exact opposite changes happen to all joints, as shown in Figure 10c, so that the head is higher than the tail to counteract falling down (Figure 11c).

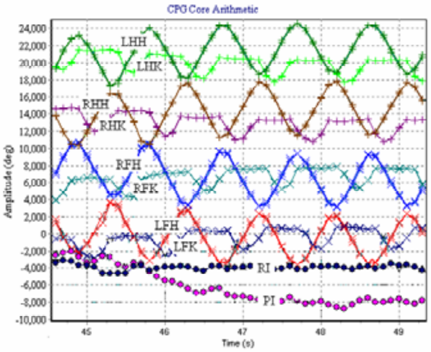
The data from the roll inclinometer are shown as the curves labeled "RI" in **Figure 10**. Here PI presents pitch inclinometer and RI presents roll inclinometer. These data quantify the inclination of the body in the roll plane, and show the robot walking steadily both up and down hill using the control algorithms discussed above. Control experiments with no postural reflex show that the robot fails to walk uphill because of serious slipping, and it walks downhill with a dangerous unsteadiness, and the likelihood of falling under inclinations larger than what we used in the experiments with the postural reflex model.



a) on the flat



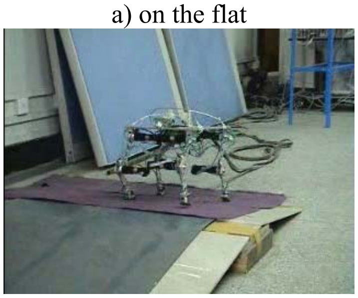
b) uphill



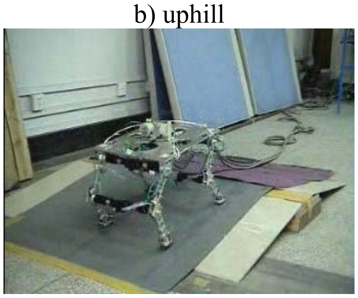
c) downhill

Figure 10 Actual reflex output curves of Biosbot walking up and down hill

a) on the flat



b) uphill



c) downhill

Figure 11 Videos of Biosbot walking up and down hill

6. CONCLUSION

In this paper, we presented a quadrupedal robot with variety of motion abilities and adaptability to the environment. The robot Biosbot has its control system derived from biological neural system of rhythmic motion and biological reflexes, such as the flexor reflex and the postural reflex. Moreover, we designed Biosbot's acts after its animal counterpart, a cat. Such control strategies endows Biosbot with good performances. It can walk in different gaits, transfer gaits, turn, clear obstacles and walk up and down hill autonomously in its environment. These movements are robust, smooth and adaptive. The study has implications for both the fundamental understanding of neural control in animals and the practical realizations of legged robots for use in the real world and social services.

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