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Biomimetic Locomotion Control of a Quadruped Walking Robot ⋆

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Abstract: In this paper, a new biomimetic control method for a quadruped walking robot is proposed. The method is derived by the observation of the gravity load receptor and stimulus-reaction mechanism of quadrupeds' locomotion, and the study of the stances on walking and energy efficiency. Though the controller is simple, it provides a useful framework for controlling a quadruped walking robot. In particular, by introducing a new rhythmic pattern generator the heavy computational burden to be paid on solving kinematics is relieved. The effectiveness of the proposed method is validated via a dynamic simulation and experimental works in a quadruped walking robot, called AiDIN(Artificial Digitigrade for Natural Environment).

1. INTRODUCTION

In spite of rapid development in robotic technologies, living creatures are still superior to robots existing currently in various aspects. Thus, it is necessary to understand the principles underlying the motions and behaviors of biological subjects for the control of robots. Mimicking living creatures currently becomes one of the worldwide trends for robotic innovations. It is considered as one of the most adequate way of developing a robot since biological systems provide a number of useful ideas concerning the control of robots. Recently, robotic researchers as well as biologists propose innovative ideas for the control of the walking robot system. Among several ideas, mimicking the rhythmic motion of animals is one of the most promising ways to control the walking robot system. By studying on this, the locomotion of the walking robot can be close to that of the real animal.

According to recent studies of neurobiologists, it is noted that a part of the neural system in the brain of animals, called Central Pattern Generator(abbreviated as CPG), produces rhythmic movements in the locomotion. Since CPG can generate rhythmic outputs even without the sensory feedback, it has been one of the most attractive approaches in the biomimetic control. On the way to study the CPG, many neural models such as McCulloch and Pitts neuron, Leaky integrator neuron, and Matsuoka neuron have been proposed by investigating neurons in the real animals' brains or bodies[1, 2]. As efforts of developing relevant methods to control robots, algorithms inspired from rhythmic patterns generators have been studied[3]. Though these neural models can illustrate the control method of animal movements, the results of applications in robotic systems are far different from real biological systems because animal's movement can not be simply mimicked with several neurons that robotic systems have introduced until now[3].

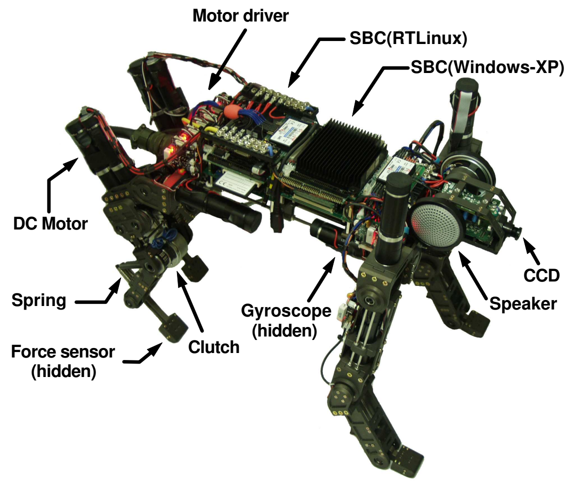

Fig. 1. AiDIN(*Artificial Digitigrade for Natural Environment*)

On controlling a quadruped walking robot, various aspects should be taken into account. In this research, several critical considerations are given for the design of a quadruped walking robot controller. Mainly, the basic principles of the quadrupedal locomotion controller are analyzed in terms of a biomimetic point of view. By the observation of the gravity load receptor, stimulus-reaction mechanism of animals are investigated using the stances on walking and posture control. The controller design factors are feedback information from several receptors and stimulus-reaction based on biological sensory system analysis. The proposed method is validated via dynamic simulation using Open Dynamic Engine(abbreviated as ODE) and then, it is

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experimentally proved by applying to a quadruped walking robot, called AiDIN.

2. DESIGN OF CONTROLLER

Usually, animals move by the actions of muscles. When muscles generate specific movements, the control action is executed via two different loops. In the first loop, a command from the brain is transmitted to the muscle through a central nervous system(CNS). In the second, the muscle reacts to external stimuli which are not predictable or recognizable. The stimuli are detected with receptors such as proprioceptor and exteroceptor[4]. Even though its structure is very complex, movements can be easily simplified by the repetitive action such as flexion and extension, because these actions are directly controlled by sensory neurons and motor neurons[5]. In this section, a locomotion controller, called *Gravity Load Controller*(abbreviated as GLC afterwards) is presented. This controller is based on a gravity load receptor and stimulus–reaction mechanism of the animal. Even though the configuration of GLC depends upon the system in hand, the basic configuration can be shared because it consists of the feedback information from several receptors and the stimulus–reaction mechanism.

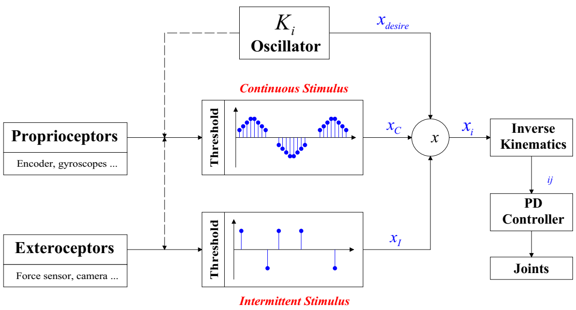


Fig. 2. The joint controller consists of four parts including an oscillator, stimulatory part, threshold detector, and PD controller

As shown in Fig. 2, GLC for the quadruped walking robot consists of four parts including an oscillator, stimulator, threshold detectors, and PD controller. In addition, the proposed controller has two loops(*exceeding* and *nonexceeding*) which are separately excited according to the threshold detector. If the information from sensory feedback(it is called *load receptor* in biology) such as force sensor, touch sensor, and gyroscope exceeds the fixed threshold value (safe region), the stimulators are activated according to the exceeding value: the *continuous stimulus* is provided when the feedbacks are around the outside neighborhood of safe region to excites the robot back to the safe state; this stimulus can be expressed as a series of pulses added continuously to the leg until the safety requirement is satisfied; besides if the feedbacks are big perturbations then the *intermittent stimulus* are generated which are usually large pulses, which propel a leg to react immediately. In the *nonexceeding* case, the stimulators are disabled and the robot only runs under the desired trajectory input.

In this paper, a new rhythmic pattern generator is proposed, which is simple and easy to implement. This study

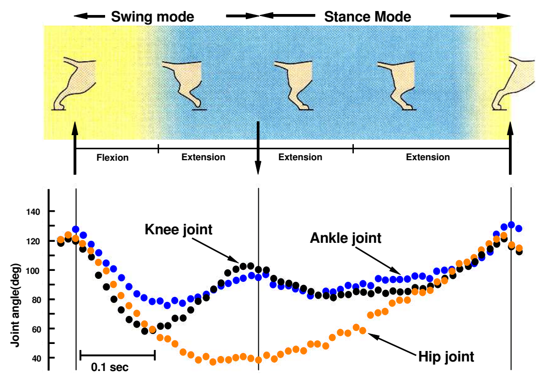


Fig. 3. Relationship between the joint angles of each leg

starts from the observation of the movements of digitgrade, typically, the ratio between *swing pase*(SW) and *supporting phase*(ST) in its walking cycle.

When a digitigrade walks in a plain environment, its limbs repeat in motion such as swinging and supporting with the nearly even intervals between their feet as shown in Fig. 3.

Also, the joint angles at each leg show a repetitive motion which maintains a regular phase between each joint angle[19]. Especially if we can understand the relationship between the joint angles in each leg, this feature can be applied to control the locomotion of a quadruped walking robot. Although many researchers have introduced that the ratio of SW vs. ST is decided according to the walking speed[6, 7], it is not easy to apply this idea to the quadruped walking robot. Previous studies note that digitigrade's walking pattern can be measured and normalized as shown in Table 1[6, 7]. Based on these ratios, a circular foot trajectories κ_i(for ith leg) can be synthesized.

Table 1. Swing mode(SW) vs. Supporting mode (ST) for one cycle

	Forelimb		Hind limb	
	ST	SW	ST	SW
Walk	0.68	0.32	0.64	0.36
Trot	0.44	0.56	0.40	0.60
Run	0.27	0.73	0.26	0.74

As a typical means, *Bezier curve* is employed in this paper. Here, κ_i can be represented as the function of time $t \in [0, 1]$ such as

$$\kappa_i(t) = \sum_{k=0}^{n} \frac{n!}{(n-k)!k!} P_k (1-t)^{n-k} t^k \qquad (1)$$

where P_k represents the kth control point. Then, the trajectory of joints in Fig. 3 can be expressed by three *Bezier curve* with four and six control points, respectively. From Eq. (1) the rhythmic pattern for the quadruped walking robot can be designed.

The rhythmic pattern generator κ generates a repetitive pattern for locomotion. It is not concerned with any sensory feedback as well as noise or disturbance. Namely, κ always generates locomotion pattern regardless of any input value as illustrated in Fig. 2. This point is different from the other pattern generator introduced until now.

Thus, it is noted that the convergence of oscillator in proposed controller is always maintained. As illustrated in Fig. 4, the overall controller for the quadruped walking robot is comprised of four joint controller and the motion is synchronized with the switch for determining the walking patterns.

The final desired position x_i of each leg is given by the stimulators and oscillator as follows.

$$x_i = \kappa_i + \delta x_C + \delta x_I \qquad (2)$$

and those are transferred into the joints space through the inverse kinematics calculation process. Then the desired joints angles θ_{ij} of leg i and joint j are controlled via PD controller at the joint level.

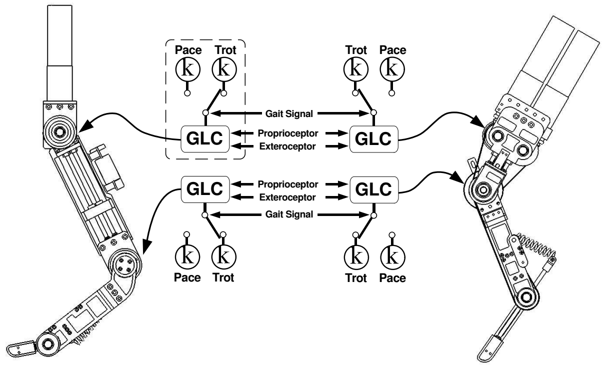


Fig. 4. Overview of the locomotion controller

3. DYNAMIC SIMULATION

To verify the proposed idea, a dynamic simulation is performed with a quadruped walking robot model. In this research, a simulator for the quadruped walking robot is developed by using Open Dynamic Engine(ODE, *http://www.ode.org*) in *Linux* environment.

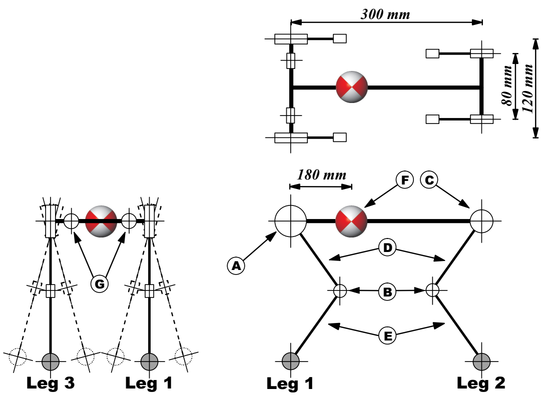
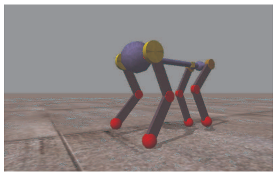


Fig. 5. Kinematic structure for simulation

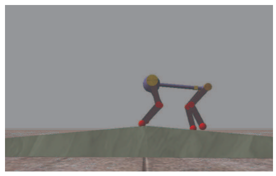
The model of a quadruped walking robot is as shown in Fig. 5 and its kinematic parameters are listed in Table 2. The model consists of 29 rigid parts coupled by 18 joints(rotational and fixed joints). The skeleton of the model contains the entire physical information in a parameterized form. In addition, limbs of the model are similar to the leg structure of the digitigrade, and the length of limbs are determined accordingly[9, 10, 11]. In particular, the forelimb has three–DOFs including the scapular joint(A), the knee joint(B), and the clavicle joint(G). The clavicle joints are necessary for the regulation of the width between the supporting feet as shown in Fig. 5. $1Kg$ of the weight is put on its vertebrate as shown in Fig. 5. In addition, *geometric similarity* with the digitigrade is adopted on determining the dimension of the robot. The length of the robot in this simulation is the same as the *specific height* of the model(about $30mm$) which is measured from the scapular joint to the hip joint[17, 11, 8]. Also, the length between scapular joints is longer than its pelvis like most of the quadrupedal mammals[12].

Table 2. Physical properties of simulation model

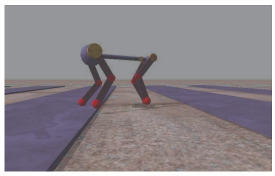
Parts	Length [mm]	Width Diameter [mm]	Height [mm]	Mass [g]
A Scapula		60	15	114
B Knee		32	15	32
C Hip		40	15	51
D Thigh	170	30	10	123
E Tibia	170	30	10	123
F Front Mass				1,000
E Clavicle		32	15	32



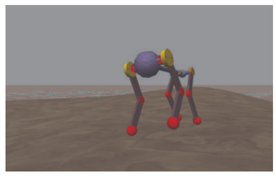
(a) Plain



(b) Slope



(c) Step



(d) Terrain

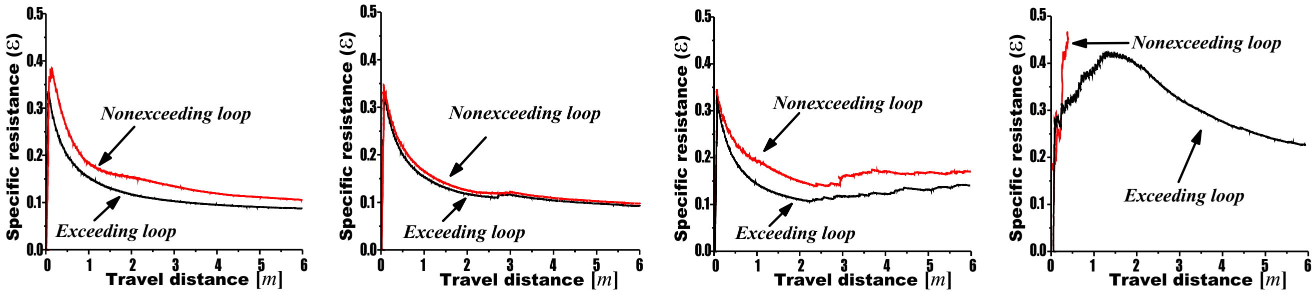
Fig. 6. (a)Plane, (b) Inclined and declined planes with a slope angle of 10°,(c) Plane with steps ($50cm \times 3cm \times 500cm$) at $50cm$ intervals,(d) Rough terrain

As shown in Fig. 6 the simulation environment can be chosen among plane, slope, plane with steps, and rough terrain, and the results of simulations are collected, respectively. To compare energy consumption of the quadruped walking robot with the proposed controller objectively, we employ a useful measure of the locomotion energetics, called *specific resistance* defined as[14, 13]

$$\epsilon = \frac{E}{mgL} \qquad (3)$$

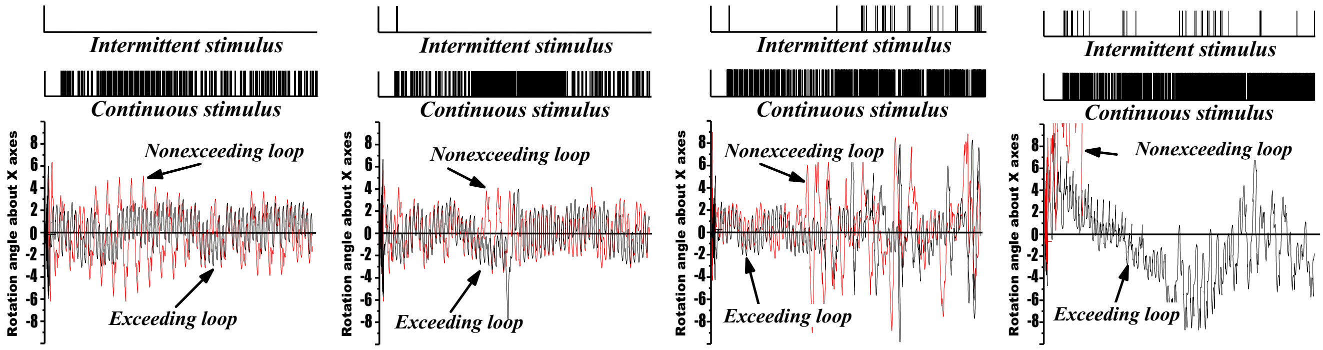
where ϵ represents the specific resistance, E means the total mechanical energy consumption for a linear displacement of L, m denotes the total mass of robot, and g is the gravitational constant. In Eq. (3), a conservative measure of energy expenditure can be represented with the integral of the absolute value of the instantaneous *shaft power*. That is, a positive torque and a negative torque are considered as total mechanical energy consumption[15].

$$E = \int |\tau_{ij}\omega_{ij}| dt \qquad (4)$$



(a) Plain (b) Slope (c) Step (d) Terrain

Fig. 7. Specific resistance versus a travel distance



(a) Plain (b) Slope (c) Step (d) Terrain

Fig. 8. Body roll angle about x axis versus a travel distance

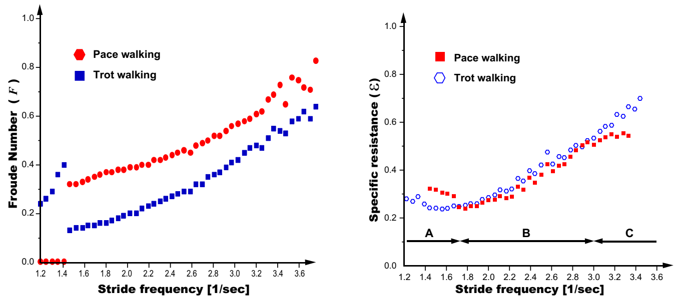
where τ_{ij} and ω_{ij} are the torque and the angular velocity of the joint j of the leg i.

Fig. 7 shows differences of specific resistances in various environments. It clarifies that the proposed controller with *exceeding loop* has greater energy efficiency than *nonexceeding loop* controller. As time goes by, the quadruped walking robot adapts itself to the environment because the robot maintains an even specific resistance as shown in Fig. 7. From Fig. 8 it is noted that the roll angle of the body in *exceeding loop* is smaller than that of *nonexceeding* . It is because *intermittent stimulus* puts the joint angles to react immediately to external sensory feedback and thus, the *intermittent stimulus* make its body stable. It implies that the central controller does not play an important role anymore if an environment becomes more complex.

As the other measure for representing the efficiency of locomotion, *Froude Number* is introduced, which is defined as

$$F = \frac{v^2}{gl} \tag{5}$$

where v means the velocity of locomotion, g is the gravitational acceleration, and l denotes a characteristic length, such as the height of the hip joint from the ground during standing[16]. *Froude Number* is roughly twice the ratio of the translational kinetic energy of the system to its gravitational potential energy during standing, as the hip height is nearly equal to the height of the mass center. Thus, *Froude Number* represents the interchange of kinetic and gravitational potential energy in the dynamics of legged locomotion[17]. Dynamic similarity is only possible if the systems have equal *Froude numbers* defined in the same way for the different systems being compared. It has been demonstrated that the transitions from walk to trot and from trot to gallop take place at approximately similar values of the *Froude Number* for the wide variety of animals.



(a) (b)

Fig. 9. (a)Froude number, (b)Specific resistance

To investigate the relation between stride frequency and *Froude number*, dynamic simulation is performed with the same model. As the stride frequency increases, F and ϵ changes accordingly as shown in Fig. 9. The energy exchange in the trot gait shows a rapid drop at the stride frequency of $1.4Hz$, but ϵ is not suddenly changed. It is noted that even though the exchange between potential and kinetic energy is not effective, the efficiency for walking can be kept for stable walking. Theoretically, in the maximum walking speed, *Froude number* is 1.0. However, the result of the simulation shows lower *Froude number* than $F = 1.0$. It is supposed that animals naturally switch from a walk or a pace to a trot at lower Froude number that $F = 1.0$[18].

4. EXPERIMENTS

A quadruped walking robot, called AiDIN (*Artificial Digitigrade for Natural Environment*) illustrated in Fig. 1 was utilized in the experiments. AiDIN contains most of the components except the power, which is supplied via a tether cable.

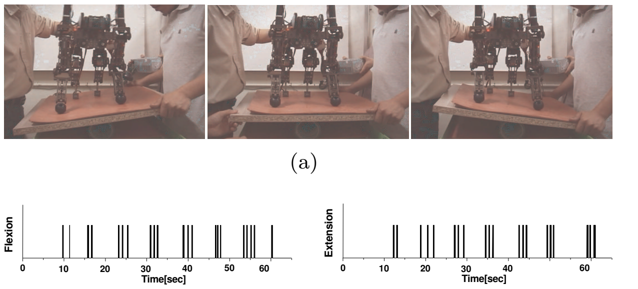
4.1 A Quadruped Walking Robot: AIDIN

As shown in Fig. 1, AiDIN has four legs with three–DOF active joints for each leg. The active joints are actuated with three geared DC motors(20 watt, gear ratio of 53 : 1), respectively. In case of the forelimb, a scapular joint is mounted to change the width between supporting feet as mentioned before. The hind limb, in particular, is equipped with a miniature clutch in the knee. It is used to switch the motion of the ankle between the passive mode and the active one. The spring in the leg that is connected between the foot and the tibia, is used as the element for storing the energy and reducing the impact on contact with the ground. Two embedded controllers(single board computer, Pentium–III 800MHz, compact flash disk) and twelve micro–controllers(PIC18f458, MicroChip) are contained in the robot. One of the controller is ported with RTLinux and twelve micro–controllers communicate with it via 1Mbps CAN protocol. The function of controller is not only to control of the walking posture, but also manage communication between micro–controllers based on CAN(*controller area network*). A voice speech engine and a vision library(OpenCV, Intel Image Processing Library) are imported in the other embedded controller(Pentium M. 1.1GHz with wireless network device). The power of the robot is supplied with a tether cable, although all the other communication is transmitted through the wireless LAN(local area network).

4.2 Experimental Procedures and Results

The locomotion controller was validated via several experiments with AiDIN. In the first experiment, self–posture changeability was tested. In this experiment AIDIN was set on a rolling plate as shown in Fig. 10(a) and the plate suddenly lurched laterally. In this case, GLC in AiDIN generated flexion or extension stimulus to make its posture stable as shown in Fig. 10(b). Even if a plate was tilted to the right or left, the robot kept its balance with GLC.

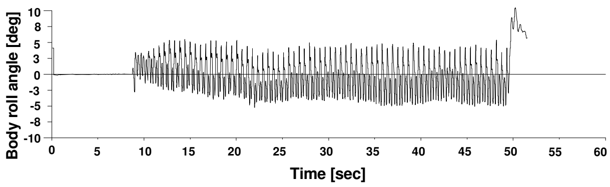
In the second experiment, a comparison between *exceeding* and *nonexceeding* loops in the proposed controller were performed as illustrated in Fig. 11. In this experiments, the robot walked in a trot gait of 20cm/sec walking speed. In the first case, the proposed controller was not fully included, but only *nonexceeding* was applied. As shown in Fig. 12(a), the body rolls with wide range of rolling angle, or even could be unstable during rolling. In this case, the robot could not walk or fall down at times. When two control loops were completely included, the robot kept balance with smaller range of rolling angle as shown in Fig. 12(b). It is noted that the robot can be controlled stably as well as efficiently with the proposed controller.



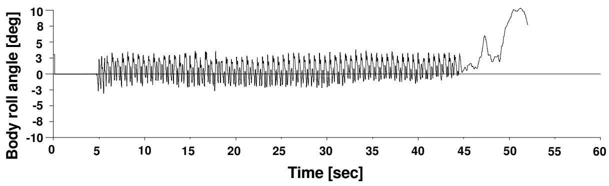
(a)

(b)

Fig. 10. Experiment to verify a self–posture changeability



(a) Trot gait with nonfeedback



(b) Trot gait with feedback

Fig. 12. Body roll angle

5. CONCLUSIONS

To mimic living creatures has been a contemporary issue in the robotics researches for long time. It may be questionable to just copy the animal, but it can be useful if the idea is explained appropriately. In this paper, we presented a biologically inspired approach on controlling a quadruped walking robot. Observation on gravity load receptor and stimulus-reaction mechanism gives us several significant tips on the control of the quadruped walking robot, which have been analyzed in terms of the robotic terminologies.

In this paper, we presented the gravity load controller with a rhythmic patterns generator included to control quadruped walking robot. Even though it is simple but it proves to be an effective controlling method in which the sensory feedback is nicely integrated with the oscillator to produce the rhythmic output signal. And it is also shown that this controller gives the robot a potential ability of adaptation in irregular environments.

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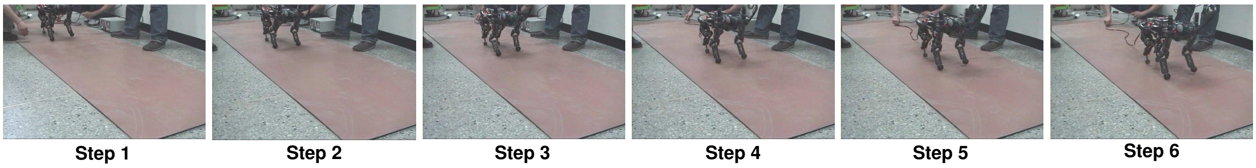
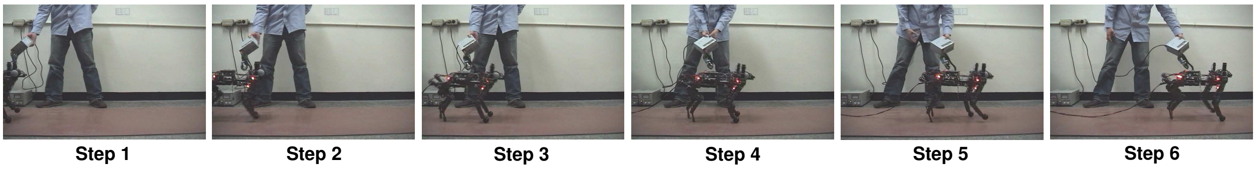


(a)



(b)

Fig. 11. Trot gait on AiDIN

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