

Rush: a simple and autonomous quadruped running robot

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The manuscript was received on 15 August 2008 and was accepted after revision for publication on 20 November 2008.

DOI: 10.1243/09596518JSCE668

Abstract: In this paper, the system design and analysis of a quadruped robot, *Rush*, are presented. The quadruped robot was fabricated to study autonomous and efficient running on flat and rough terrain. It is a compact, kneed, four-legged machine with only one actuator per compliant leg. A novel control strategy for the quadruped robot has been proposed in consideration of several engineering limitations on sensory feedback. Several simulation studies have already been performed to confirm the validity of the control strategy in the previous reports. In this paper, the results obtained from experiments with *Rush* are found to agree with the simulation results. The reported work may help improve the understanding of energy-efficient running locomotion and the simple control required to autonomously stabilize it on flat or rough terrain.

Keywords: quadruped running robot, delayed feedback control (DFC), rhythm generator, torque generator

1 INTRODUCTION

Since the work of Raibert in the 1980s and 1990s [1, 2], the concept of active dynamics and balance has added insight into legged locomotion and the design of legged robots. Heretofore, many studies of legged robots, in particular running robots, have been performed under the influence of the concept. An ambulatory robotics group led by Buehler at the McGill University respectively developed their monopod robots (i.e. Monopod I and II) and quadruped robots (i.e. Scout I and II) [3]. Furusho *et al.* realized bounding locomotion in a quadruped robot with articulate-joint-type legs [4]. More recently, the combined group of Stanford and Ohio State Universities also manufactured a quadruped galloping machine *KOLT*, which was similar in size to a large goat and engaged the direct adaptive fuzzy control with good response [5]. In Hirose's robotics laboratory, a jumping quadruped robot *AirHopper* driven by pneumatic power was also developed [6].

In addition, a hybrid wheeled-leg robot *PAW* has been developed by Smith's group [7]. Although only wheeled mobility is performed on the robot at present, it is still worth expecting it to supply and improve legged mobility in the future.

On the other hand, since animals own the robustness and versatility needed to operate in unstructured environments, several legged robots take design inspiration from biology. Hyon and Mita manufactured a monopod hopper *Kenken* by imitating the musculoskeleton of the leg of a dog [8]. Based on a different concept, Kimura *et al.* respectively developed the running robot *Patrush* and walking robot *Tekken* series, which are controlled by principles from neurobiology [9, 10]. It is important to note that these robots from Kimura's group are good realizations and attempts concerning control based on biological concepts and not simple imitations about the mechanisms. In fact, the most famous instances are two hexapod robots, *Sprawlita* [11] and *RHex* [12], which are inspired by discoveries about the self-stabilizing properties of insects. They combine passive-dynamic-based stabilizing with sensor-based adaptation to accomplish running over rough terrain.

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Although many researches have been conducted on running of legged robots, to the best of the authors' knowledge, a few researches emphasize autonomously and efficiently generating and stabilizing running on flat or rough terrain. This research aims at constructing an autonomous quadruped running robot, referred to as *Rush*. The goals of the study are twofold: (1) to realize steady running with good energy efficiency and (2) autonomously to suppress such disturbances as rough terrain. In a previous paper [13], a novel control strategy, consisting of a rhythm generator and a torque generator with delayed feedback control (DFC), has been proposed to accomplish the purpose. Several simulation studies have already been performed to confirm the validity of the control strategy. The simulation studies produced the following results.

1. When a robot runs on flat terrain without disturbance causing energy loss, the self-stabilization property is sufficient.
2. When a robot runs from a standing state or runs up a small step, the self-stabilization property is not sufficient and the proposed control strategy is effective.
3. When a robot runs over a slope, the energy relative to the touchdown ground always changes. Thus, the additional control method using sensory information is necessary and essential.

In this paper, section 2 mainly introduces the design concepts concerning hardware and control systems for the small and autonomous quadruped running robot *Rush*. By using the designed quadruped robot and the proposed control strategy as shown in sections 3 and 4, some experiments are carried out where the robot runs from standing to steady bounding on flat terrain with good energy efficiency and successfully runs up a small step. These experimental results described in section 5 agree with the corresponding simulation results reported in the previous papers of this study [13, 14]. In section 6, two significant topics (i.e. control concepts from neural biology and for unifying walking and running functions for the single-legged robot) have been discussed. Finally, conclusions of the paper are described in section 7. It is important to mention here that this work attempts to summarize some design approaches about a legged robot running on flat or rough terrain and challenges to simplifying sensory feedback on the designed robot. As a result, *Rush* provides a good demonstration of such attempts.

2 DESIGN CONCEPTS

In this section, the design concepts necessary for adaptive running on flat or rough terrain are briefly described.

2.1 Considerations for legged running control

In general, stable running can be considered to be rhythmic motion. Full and Koditschek [15] also pointed out that rhythmic motion is mainly generated by the spring-mass system in high-speed running and that the self-stabilization property of a mechanism can cancel disturbances to a limited degree. In other words, the dynamics of the mechanism (e.g. the self-stabilization property) should be adequately emphasized when a running robot is designed. In addition, during rapid locomotion such as running, the response time of the control system is shortened. Thus, the complex feedback control is unsuitable for rapid locomotion because it will spend more calculation time. However, even though a few researchers suggest only using open-loop/feedforward control during rapid locomotion [15, 16], the authors argue that the proper sensory feedback is still essential and necessary when a robot confronts a transition of states (e.g. from standing to steady running) or an unstructured environment (e.g. irregular terrain) because the open-loop/feedforward cannot provide adaptive adjustments. Motivated by many researchers' suggestions [16–20], the authors reported on several studies in relation to the self-stability of the quadruped mechanism in their previous article [14].

Since the self-stability is sufficient for running in the steady state, not only the control system can be simplified but also good energy efficiency can be obtained by utilizing the self-stabilization properties of the mechanical system [20]. However, the self-stability is insufficient for adapting to transient states or such disturbances as irregularities of the terrain. Thus, a control method using sensory information is essential in order to realize the transition from standing to steady running or stable running on rough terrain.

2.2 Considerations for hardware design

It is important to note that the hardware systems of a legged robot (i.e. mechanical system and electronic system) should be well designed in considerations of (a) energy efficiency, (b) adaptation to irregular terrain, (c) shock resistance, and (d) system mobility and

expandability. In particular, the designs of the leg mechanism are more significant because they can influence the performance of dynamic walking and running (e.g. maximum moving speed, energy efficiency, adaptability on irregular terrain, and so on). Based on the above-mentioned four issues, the authors took the following design concepts into account when designing and fabricating the *Rush* quadruped robot.

1. A smaller gear reduction ratio is necessary. Although the large gear reduction ratio provides good amplification of torque, an immoderate reduction ratio will produce undesirable viscous friction of the joints. Then, more energy will be consumed to drive the stiff joints. In addition, the joints with a small gear reduction ratio have high backdrivability (i.e. no self-locking) so as to increase passive compliance of joints.
2. Make the most of passive compliance. In other words, it is important to enhance the viscoelasticity of the leg. Adequate viscoelasticity can provide efficient energy conversion (i.e. store and return elastic energy) during the cyclic running period and a good self-stability property [15, 21]. In fact, the compliance of the leg is different during the swing or stance period. Thus, designing a leg mechanism with adjustable viscoelasticity is a significant attempt.
3. Decrease mass and inertia moment of the leg, especially that of the lowest link of the leg. It is advantageous to abate the impact of the leg on the ground and quicken its motion and response.
4. Decrease the contacting area at the end of the toe. This means that the touchdown area of the leg should be minimized in order to adapt to the limited touchdown space on an irregular terrain. Furthermore, it can also reduce the influence from the terrain.
5. A compact, high-performance, and small-sized electronic controller is necessary. Since it is desirable to fabricate an autonomous and untethered running robot, all computations should be implemented online. Therefore, all electronic systems, including the computer and sensors, should be embedded into the robot. Moreover,

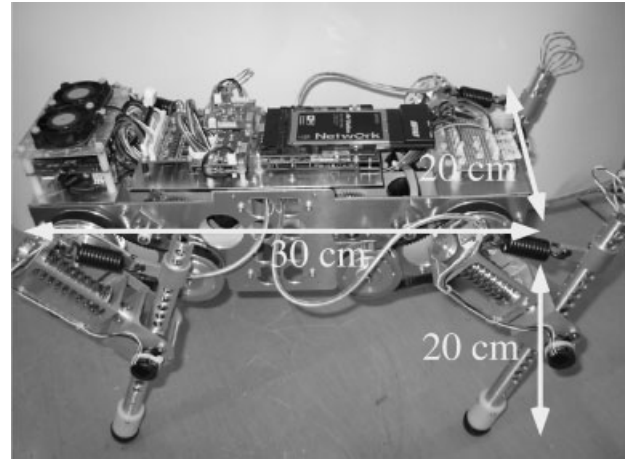


Fig. 1 A quadruped running robot *Rush*. The size is 30 cm in length and 20 cm in width. The height of the leg is 20 cm. The total weight is 4.3 kg

the selected electronic controller should have enough input/output (I/O) ports to satisfy future expandability requirements. Even though this study is a challenge to simplify sensory feedback and active driving, it is still desirable to increase adequate sensor feedback and actuation in order to accomplish three-dimensional motion or adaptation to a more irregular terrain.

3 HARDWARE

Figure 1 shows the robot *Rush*, which is used to study autonomous running. Its main parts are a rigid body and four compliant legs, connected by hip pitch joints. The body consists of a platform that carries actuators, transmission devices, and board computer interface electronics. The total weight of the robot is 4.3 kg. The length and width of the body are 30 and 20 cm respectively. The height of a leg is 20 cm when the robot stands. The dimensions of the *Rush* quadruped robot are consistent with those of the quadruped model performed in the previous study. They are designed to match visually the dimensions of the Japanese Midge Shiba dog. The more detailed values of physical parameters are presented in Table 1.

Table 1 The physical parameter values of the designed quadruped robot *Rush*

Parameter	Value	Unit	Parameter	Value	Unit
Total mass	4.3	kg	Body length	0.3	m
Body width	0.2	m	Upper leg length (uncompressed)	0.08	m
Lower leg length	0.148	m	Standing height	0.2	m
Motor power	27.5	W	Motor torque constant	70.4	mNm/A
Motor armature constant	12.5	Ω	Reduction ratio in hip joints	19	n/a
Spring constant in knee joints	20	kN/m	Direct-acting spring constant	7.4	kN/m

The design of *Rush* is a challenge to simplify sensory feedback. Thus, only encoders and contact sensors are respectively attached to each joint and toe in order to measure the rotary angles of joints and the stance phase period. Although this sensor configuration is sufficient for controlling and stabilizing quadruped running as described in this paper, the authors still plan to add two rate gyro sensors in order to measure the body pitch and roll angles. The reason for adding the rate gyro sensors is to adapt to the high-level irregularity of the terrain (e.g. slope or big obstacle) [22]. Since *Rush* is designed for running, several issues (e.g. the efficient exchange of energy, alleviation of impact damage, load decrease, etc.) have to be taken into account. Thus, it is very necessary to design a compliant leg and construct a compact controller for a running robot.

3.1 Leg mechanism description

As illustrated in Fig. 2(a), the leg consists of an upper and a lower part. Both parts are considered to be a chain of two rigid segments with a spring about 20 kN/m, so the knee joint is always passive. The toe is narrow, using a hemispheric hard gum and providing a good approximation to a point of support. In the upper part, a special mechanism, referred to as a direct-acting spring device (see Fig. 2(b)), is mounted to absorb impact force, so the impact damage acting on the shaft of each joint

during rebound with the ground can be alleviated. Each hip is actuated by a d.c. motor of 27.5 W power, a three-stage planetary gearbox, and a belt and pulley pair, with about a 19 reduction ratio, providing good amplification of the torque and compliance of the joints. In addition, a belt and pulley pair can also isolate impact forces from the motor shaft.

3.2 Electronic controller description

Since a robot such as *Rush* has to fulfil several special operations (e.g. sampling sensors, driving motors, and so on) when running, its controller is required to be not only multifunctional but also real-time. Moreover, the controller is equipped at the body of the robot, so a light and compact device is also required. Therefore, the *Rush* robot employs a specially made computer system as the electronic controller. The computer system called TITech-Wire includes a compact controller equipped with wireless local area network (LAN) and a high-speed serial bus that connects several serial I/O nodes in cascade. Through such a serial bus, the add-on analogue and digital I/O interfaces can be easily equipped. The TITech-Wire installed in *Rush* contains three major modules (i.e. root control module, analogue-to-digital (A/D) module, and digital module), as shown in Fig. 3. The root control module consists of a central processing unit (CPU) module (AMD Elan520 133 MHz), a PC card controller

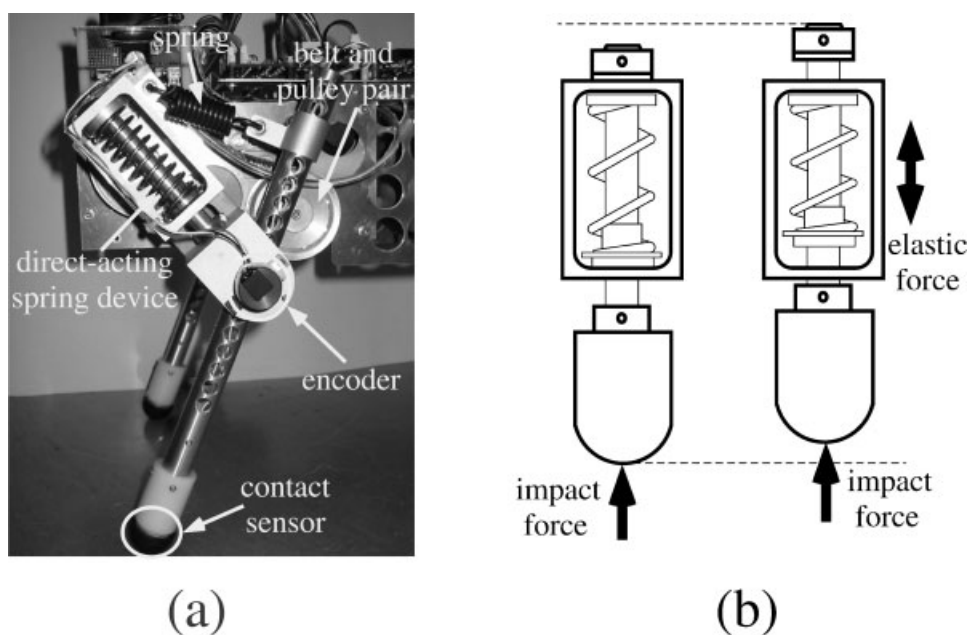


Fig. 2 The design of a compliant leg. It has two main parts, an upper and a lower part, connected via a spring (20 kN/m): (a) photograph, (b) a direct-acting spring device is capable of absorbing and impact force during the stance period

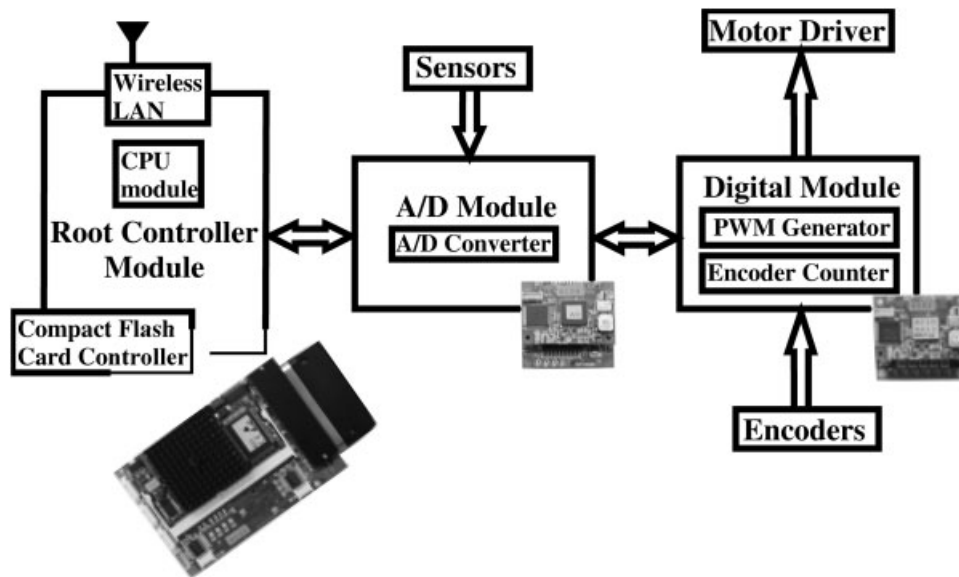


Fig. 3 The computer system includes a compact controller equipped with wireless LAN and a high-speed serial bus that connects several serial I/O nodes in cascade

driving the wireless LAN card, and a compact flash card controller. Analogue signals of various sensors are interfaced throughout the A/D module. The digital module generates pulse width modulation (PWM) signals to control rotation of the motors, and counts the angular information from each encoder attached to each joint. In order to obtain real-time ability, the authors take advantage of a real-time system (i.e. RTlinux) based on the Linux operating system. Thus, the abundant developing tools in Linux can be applied to developing the control program of *Rush*.

4 CONTROL METHOD

As described in section 2.1, it is worth expecting the hypothesis showing that the rhythm and gait of running are governed by the spring-mass system in the steady state (e.g. stable running) and generated and adjusted by the rhythm generator in the transient state (e.g. shifting from the standing state to the stable bounding state or running up a small step). Thus, it should be considered that running control may take advantage of the dynamic properties. In this study, the authors first consider quasi-passive running in a bounding gait with no energy loss, and use a fixed point of a *Poincaré* map as the desired motion. The steady running at a fixed point has two advantages that utilize the dynamic properties of the mechanism. One is energy efficiency. The other is self-stability. To cause the motion of a

quadruped robot to converge to the fixed point under energy loss and disturbance, the authors next apply the coupling between control and mechanical systems to stabilizing and adapting. More concretely, the control system consists of a rhythm generator and a torque generator combined with sensory feedback referred to as 'delayed feedback' [23]. As a matter of fact, the concept from neurobiology has been accepted in a few legged robot researches concerning motion generation and motion adaptation [10–12]. Note that the coupled dynamic system can induce autonomous adaptation based on its own dynamics under changes in the environment (e.g. adaptive running on irregular terrain). Therefore, the proposed control method avoids such serious problems in robotics as modelling of the mechanical system and environment, conflict between planned motion and actual motion, and so on.

On the other hand, the stabilization of the rhythmic locomotion can be considered to be a control issue concerning convergence on a fixed point. It is similar to the concept of delayed feedback control (DFC) in the field of chaotic control. Inspired by the concept, Sugimoto and Osuka selected the kinetic energy on the impact point as the controlled variable of the DFC method to stabilize the biped quasi-passive dynamic walking in simulations [23]. However, since an energy-based controller is inadequate when it comes to practical application [13], the authors modified Osuka's DFC method and

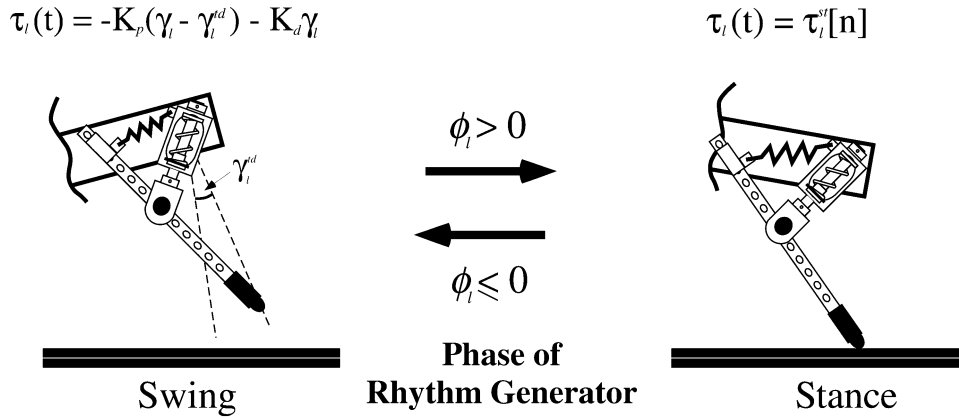


Fig. 4 Switching of the hip joint controller according to the output phase ϕ_1 of the rhythm generator

proposed their original control method of quadruped bounding for an actual robot.

4.1 Rhythm generator

The authors define the phase of each leg in the n th step ϕ_1 as expressed by

$$\phi_1 = \sin(\omega_1[n]t + \psi_1) + \phi_{01}, \quad \omega_1[n] = \frac{2\pi}{T_1[n]} \quad (1)$$

The timing for each leg to switch between the stance and swing phase is $\phi_1 > 0$: swing phase, $\phi_1 \leq 0$: stance phase (see Fig. 4), where $T_1[n]$ and $\omega_1[n]$ are the cyclic period and the angular frequency of the leg l in the n th step respectively. The initial phase ψ_1 is defined for the generation of the gait. (The bounding gait: $\psi_f = 0$, $\psi_h = \pi$ and the pronking gait: $\psi_f = \pi$, $\psi_h = \pi$ where 0 and π mean that the leg begins to move from the swing phase and stance phase respectively.) The offset ϕ_{01} determines the duty factor. $T_1[n]$ is calculated by using the DFC method described in section 4.3.

4.2 Torque generator

Depending on the leg phase ϕ_1 generated by the rhythm generator, the following different control actions are assigned as shown in Fig. 4.

1. In the swing phase ($\phi_1 > 0$), the following proportional-derivative (PD) control is performed

$$\tau_i(t) = -K_p(\gamma_i - \gamma_i^{td}) - K_d\dot{\gamma}_i \quad (2)$$

2. In the stance phase ($\phi_1 \leq 0$), constant torque $\tau_1^{st}[n]$ of the hip joint in each leg is output, as expressed by

$$\tau_i(t) = \tau_i^{st}[n] \quad (3)$$

In the control action of the swing phase, γ_1^{td} is the desired leg angle relative to the body, which is selected from the fixed point and not adjusted online. K_p and K_d are the gains of PD control. In the control action of the stance phase, the DFC method described in section 4.3 determines $\tau_1^{st}[n]$.

4.3 DFC with stance phase period

The properties of delayed feedback control motivate the control method of quadruped bounding described here. It is advantageous to use a DFC method that results in a steady state cycle. As outlined in the previous section, the authors use the stance phase period as sensory feedback of the DFC method since the stance phase period is easy to measure accurately. Hence, the proposed DFC methods are as follows

$$T_1[n+1] = T_1[n] - K_{DF-T}(t_1^{st}[n] - t_1^{st}[n-1]) \quad (4)$$

$$\tau_1^{st}[n+1] = \tau_1^{st}[n] - \delta(l)K_{DF-\tau}(t_1^{st}[n] - t_1^{st}[n-1]) \quad (5)$$

where

$$\delta(l) = \begin{cases} -1, & l = f : \text{foreleg} \\ 1, & l = h : \text{hindleg} \end{cases}$$

where K_{DF-T} and $K_{DF-\tau}$ are DFC gains. They are decided by trial and error in experiments. Equations (4) and (5) are used to calculate the cyclic period of the leg phase and the torque of the hip joint of the next stance phase respectively. The used parameters

Table 2 The parameter values of the controller used in experiments

Parameter	Value	Parameter	Value
ψ_f	0	ψ_h	π
ϕ_{of}	0.16	ϕ_{oh}	0.09
$\gamma_f^{td}(\text{rad})$	0.524	$\gamma_h^{td}(\text{rad})$	0.838
$K_{DF:T}$	0.12	$K_{DF:\tau}$	6.8
$K_p(\text{N m/rad})$	10	$K_d(\text{N ms/rad})$	0.02

of the control method in the following experiments are listed in Table 2.

5 EXPERIMENTAL RESULTS

5.1 Transition from standing to steady bounding

To validate the proposed control strategy stated in the previous report [13], the authors utilize the quadruped robot *Rush* to implement an experiment in which *Rush* runs from the standing state to the steady bounding state on a flat terrain. In order to generate the bounding gait, the authors adopt $\{T_f[0], T_h[0], \tau_f[0], \tau_h[0]\} = \{0.20, 0.69, -1.8, 1.8\}$ as the initial condition of the DFC method expressed by equations (4) and (5). The initial values of $T_h[0]$ and $\tau_h[0]$ are much larger than those in the steady state for providing sufficient kinetic energy during the first stance phase period of hind legs.

Figure 5 presents snapshots of *Rush*'s bounding locomotion on flat terrain with the proposed control strategy. As shown in Fig. 6 (left), the phases of the rhythm generators and the legs are synchronized and converge on the bounding gait. It is apparent here that the 180° phase difference between the fore and hind legs has been caused from about 4.5 s. Figure 6 (right) illustrates that the running period $T_i[n]$ generated by a rhythm generator accords with that measured through a contact sensor after the 15th step. Note that the experimental results, especially the transitional patterns of the cyclic period of rhythm generators and legs, agree well with those results in simulations shown in reference [13].

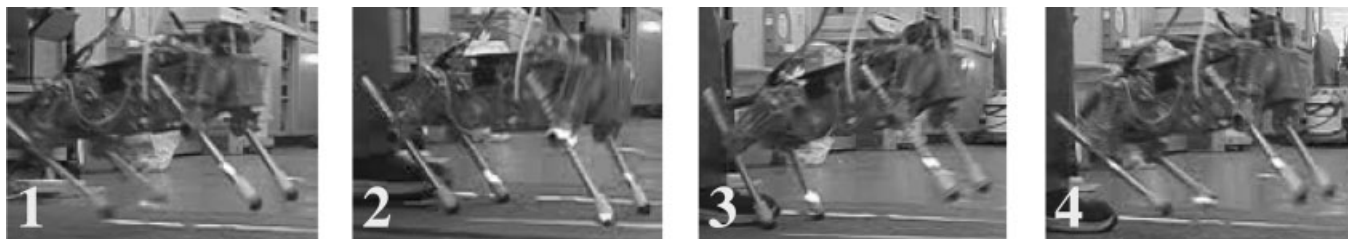
**Fig. 5** Snapshots of the *Rush* quadruped robot running in the bounding gait

Figure 7 shows test results of the torque generators implemented in *Rush* running on flat terrain. The left graph shows output values during the whole bounding period. The right graph shows constant torque of the hip joints during the stance period as a function of steps. Note from the right graph that, although the constant torque during the initial stance phase period is set at a larger value (i.e. -1.80 and 1.80 N m), the last steady torque still converges to a minor value (i.e. -0.85 and 0.93 N m) since the DFC method in torque generators works effectively. The convergence value of torque is higher than the value in simulation reported in reference [13] and results in a somewhat higher energy consumption. However, when considering modelling errors of collision and friction, the somewhat higher energy consumption is still considered to be very energy efficient. It is important to mention that such a torque adjustment in the process of state transition has not yet been reported in the stable legged robot literatures.

As a result, the experimental running period is approximately 0.30 s, the average forward speed is 0.9 m/s, and the maximum heights of toes (i.e. clearance) in fore and hind legs are respectively 5 and 4.5 cm. Note that a hand-held chronometer was used to calculate forward speed and was not measured online. In addition, the jump-height and clearances are measured by visual observation in the video of the experiments. Although such measurements are not very accurate due to many errors, the measured results may still be approbated because the proposed control strategy for *Rush* does not directly use these measured state variables as sensory feedback.

5.2 Running in different conditions

In order to evaluate the proposed control strategy for the quadruped robot *Rush*, the authors should look at the factors that affect its performance and see whether the same basic control and mechanical systems are robust. Figure 8 shows the *Rush* perfor-

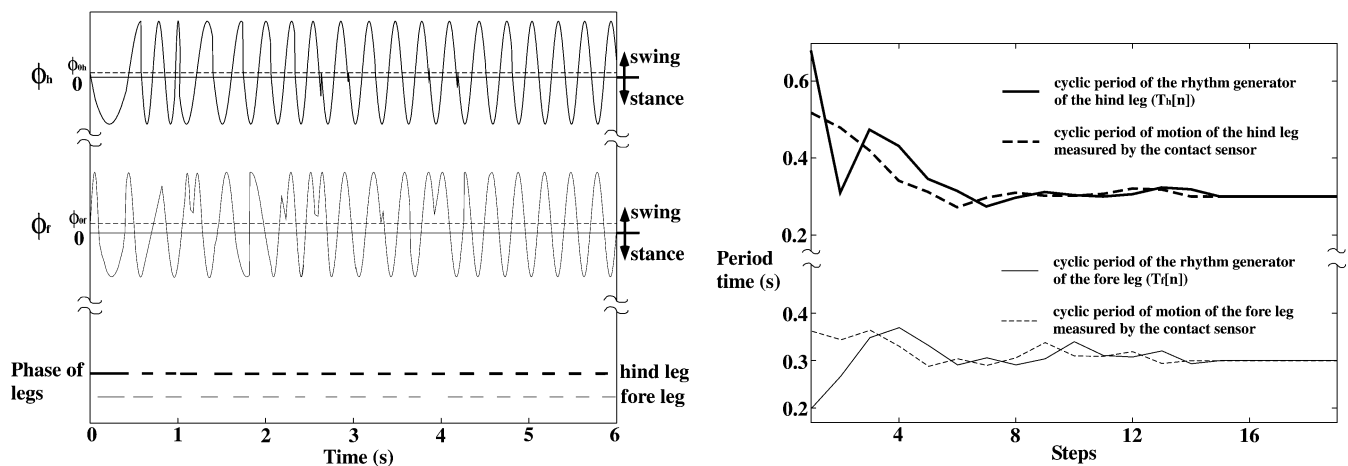


Fig. 6 The experimental results of DFC in the transition from standing to steady bounding. The output phase of the rhythm generator and the phase of the leg measured by the contact sensors are shown in the top graph. The cyclic period of the rhythm generator and the cyclic period of leg motion measured by the contact sensor are shown in the bottom graph. The experimental running period is approximately 0.30 s

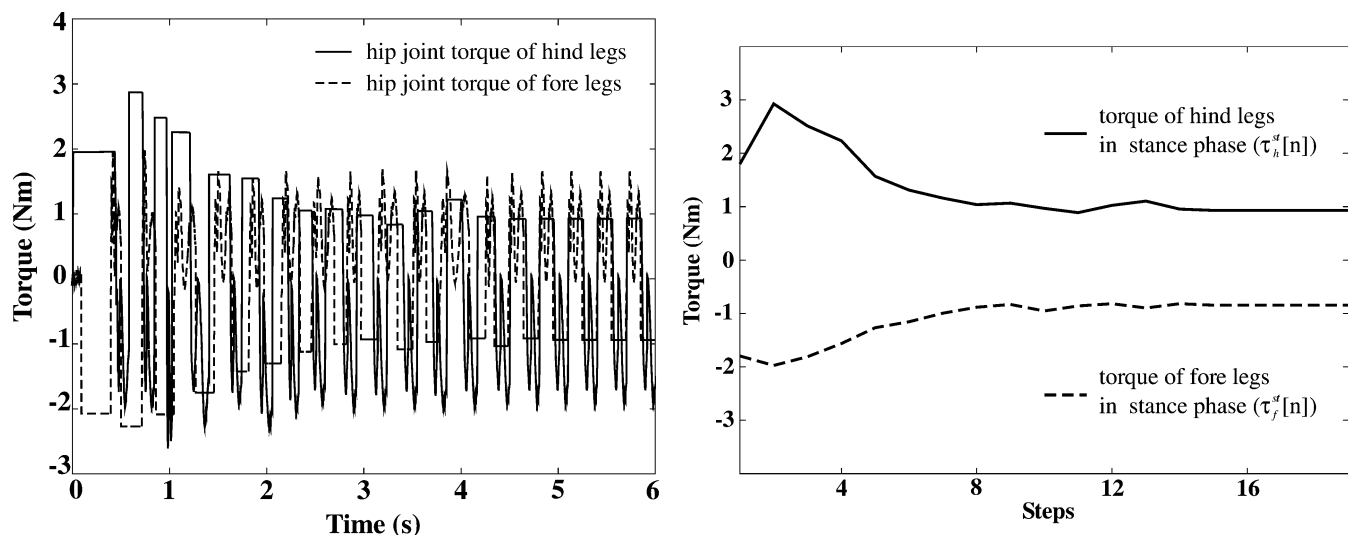


Fig. 7 Torque of the hip joints in the fore and hind legs when *Rush* is running on flat terrain from standing to steady bounding. The left graph shows output values during the whole bounding period. The right graph shows constant torque of the hip joints in each stance phase

mance results (i.e. cyclic period of the motion of legs and hip joint torque during the stance period) as a function of steps for three different cases. The bold solid lines represent the results when *Rush* runs from standing to steady bounding on an artificial lawn without any load. The thin solid lines are for the same condition, but with a 0.5 kg load. The dashed lines are for *Rush* running on concrete ground also without any load. As shown in Fig. 8, although the same initial conditions of the DFC method as listed in section 5.1 are used, the cyclic period of motion of legs and hip joint torque in a stance phase converge

upon the different steady states due to the fact that the different surfaces of the ground and loads cause different friction and collisions. As plotted in Fig. 8, the longer cyclic period and larger torque occur when *Rush* runs on an artificial lawn. Of course, in terms of a robot with loads, it is necessary to extend the cyclic period properly and increase hip joint torque. Since the friction and collisions are considered to be disturbances around a fixed point in the proposed control strategy [13], it means that the designed quadruped robot with the proposed control strategy has a good antidisturbance capability.

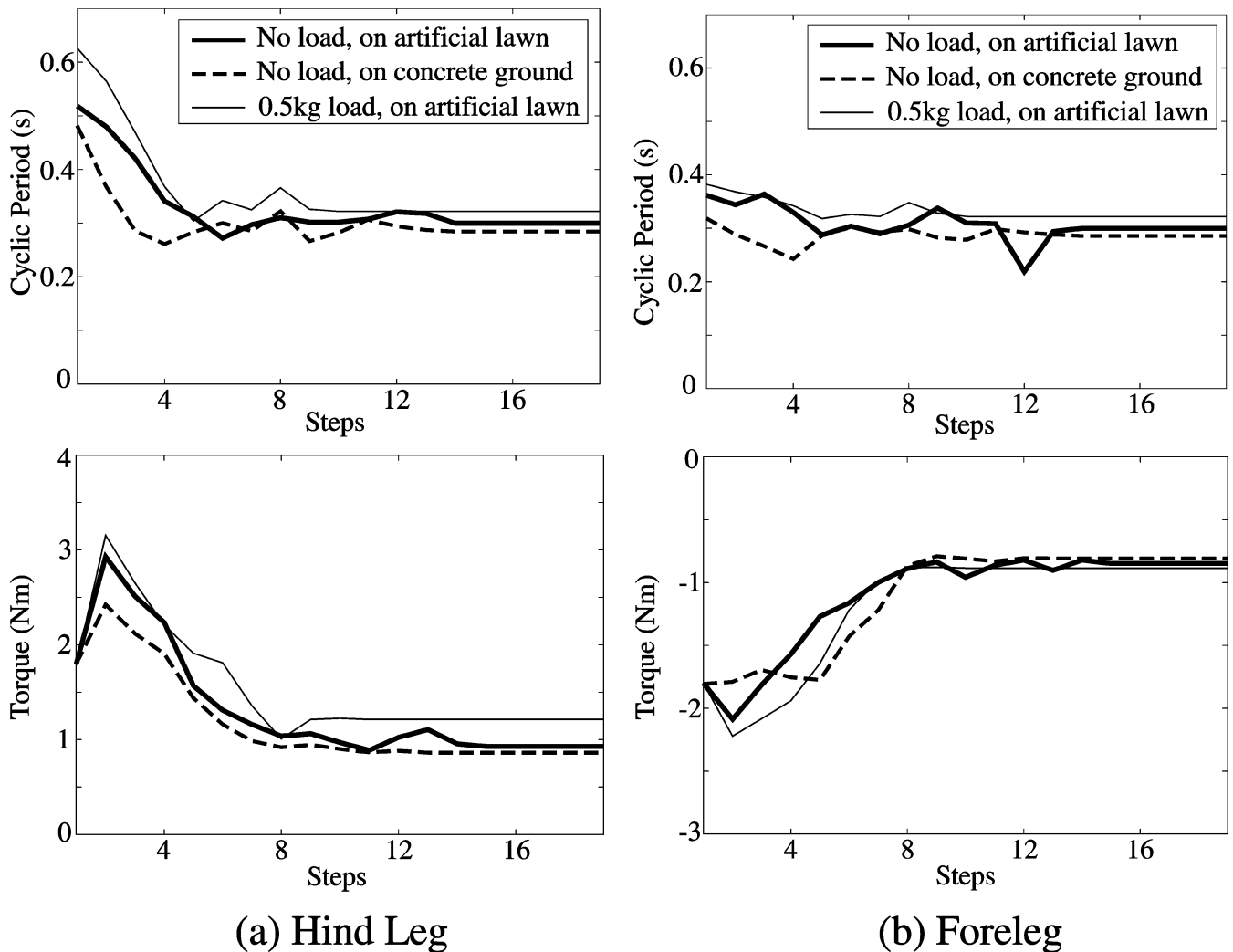


Fig. 8 The performance results as a function of steps when *Rush* runs from standing to steady bounding for three different cases

It is important to mention that *Rush* runs at almost identical forward speeds and jump-heights in the above-mentioned three different cases. As reported in many researches concerning self-stabilization properties of mechanisms [12, 17, 18, 20, 24], there is a symmetric motion of the body with respect to the foot when the foot is placed in the neutral position. Namely, the legged machine, for certain touchdown angles, can follow a cyclic motion. It provides a rational explanation for the above-mentioned phenomena because the same desired touchdown angle is used in the three different cases.

5.3 Evaluation of energy efficiency

The specific resistance is a measure of the energetic efficiency usually employed to compare the performance of different kinds of vehicles. It was originally

proposed by Gabrielli and von Karman [25] and widely applied to the robotics evaluation of the energy efficiency by Buehler and his colleagues [3, 20, 26]. The specific resistance is defined as the ratio of power output $P(v)$ and the product of moving speed v and weight of the robot, mg

$$\varepsilon(v) = \frac{P(v)}{mgv} \quad (6)$$

In the *Rush* quadruped robot, $\varepsilon(v) = 0.66$ at an average moving speed of about 0.9 m/s. According to the classification offered by Buehler's research group, it can be stated that the *Rush* robot is the most efficient quadruped machine. Some relevant quadruped machines to compare are Raibert's running quadruped robot ($\varepsilon(v) \approx 10$ for $v \approx 1$ m/s), Scout II robot ($\varepsilon(v) \approx 1.5$ for $v \approx 0.9$ m/s) [26], and KOLT robot ($\varepsilon(v) \approx 1.18$ for $v \approx 1.1$ m/s) [27]. In

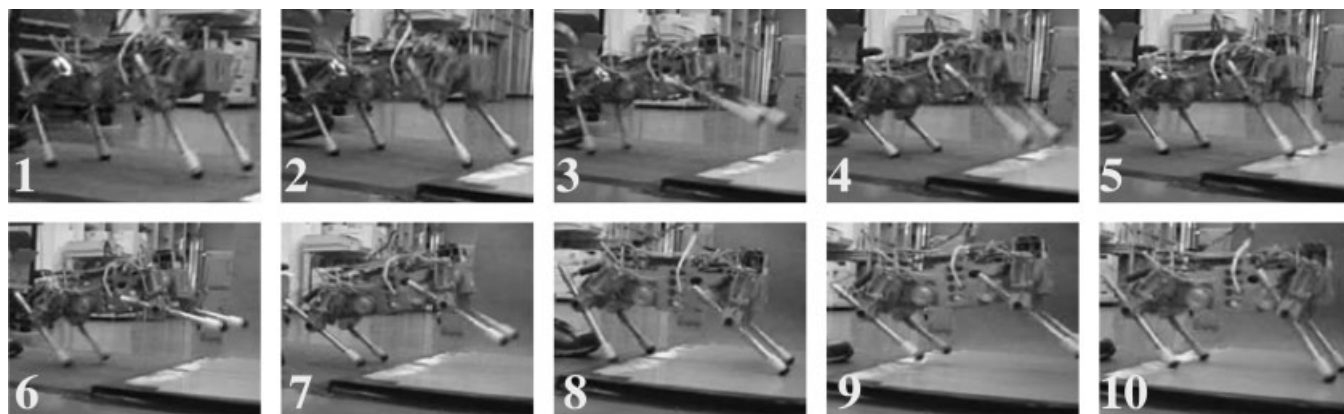


Fig. 9 Snapshots of the *Rush* quadruped robot running up a 2 cm height step

addition, the specific resistance of two quadruped walking robots (i.e. *Tekken I* [10] and *Tekken II* [28]) developed in the authors' research group have already been investigated. As a result, the specific resistance of the *Tekken II* robot ($\varepsilon(v) \approx 1.5$ for $v \approx 0.7$ m/s) is lower than that of *Tekken I* ($\varepsilon(v) \approx 2.1$ for $v \approx 0.7$ m/s) because the former is equipped with a spring device in each leg so as to facilitate the energy exchange. It is indicated that a spring device plays an important role in improving the energy efficiency of a legged robot.

5.4 Running up a small step

In the recent experiments, the *Rush* robot first runs stably on a flat terrain at 0.9 m/s with a bounding gait. Next, the robot runs up a 2 cm height step. Under the function of the proposed control method, the *Rush* robot successfully mounts the step and continues bounding at the initial speed. Figure 9 shows the snapshot illustrating the motion.

Figure 10 shows the cyclic periods of the rhythm generator and practical motion. When the robot runs stably, its cyclic period of the rhythm generator identifies with that of practical motion measured by the contact sensors at toes. In the 13th step, the *Rush* quadruped robot runs up a 2 cm height step. Since the stance phase period is fed back to the rhythm generator through DFC, the rhythm generator and the practical motion of the leg are mutually entrained. When the robot fully mounts the step in about the 27th step, the cyclic periods of the rhythm generator and practical motion reconverge at the initial value (i.e. 0.3 s). It means that the *Rush* robot runs stably over again. The same transition also appears in the hip joint torque in the stance phase, as shown in Fig. 11. As soon as the DFC works for the torque generator, the output of the actuator will be

adaptively adjusted so as to reconverge at the torque of the stable status.

These experimental results demonstrate well those of simulation studies. As compared with the results of both studies, it can be concluded that the proposed control method helps to adapt actively to the low-level irregularity of terrain.

6 DISCUSSION

6.1 Inspiration from biological concepts

The proposed control method is loosely inspired by biological concepts. As the biological studies of

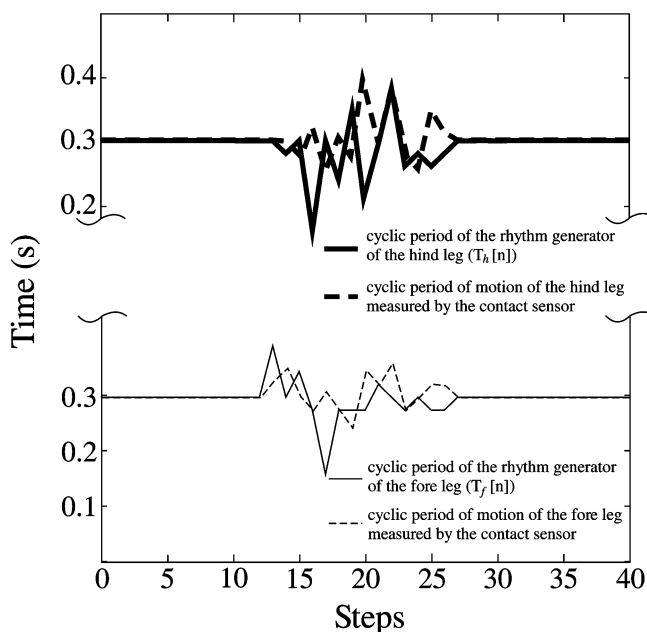


Fig. 10 The experimental results concerning running up a 2 cm height step with the proposed control method. The period of a single step is approximately 0.3 s

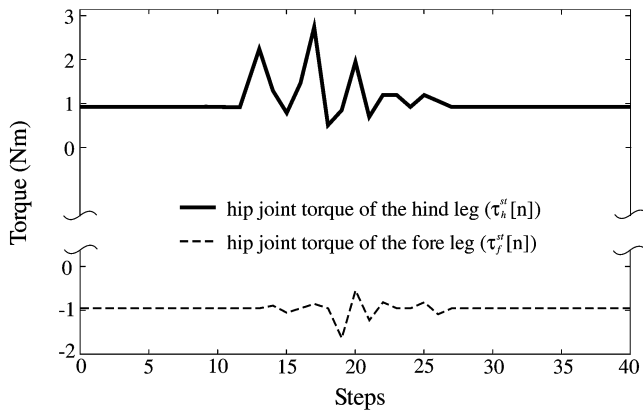


Fig. 11 The experimental results concerning running up a 2 cm height step with the proposed control method. The hip joint torque in the stance phase are respectively 1 N m (hindleg) and -1 N m (foreleg)

motion control have progressed, it has become generally accepted that animal rhythmic motion (e.g. swimming, fly, walking and running) is mainly generated at the spinal cord by a combination of a CPG (central pattern generator) and reflexes receiving adjustment signals from the cerebrum, cerebellum, and brain stem [29, 30]. Such a biological control concept has considerable merit as there is no adaptation through motion planning. Neural and musculoskeletal systems are coupled to each other, generating motion by interacting with the environment emergently and adaptively.

In this study, an oscillator referred to as a rhythm generator is employed to generate the basic running pattern where the running gait can be decided by adjusting the phase difference among the different oscillators. The stance phase period measured by the contact sensor is fed back to the phase generator by using DFC. As a result, the coupled running pattern can be generated emergently and adaptively. It is remarkably similar to CPG and a response in physiology. Note that the simple trigonometric function is sufficient for generation and adjustment of the running pattern. The motion pattern on the level of the CPG (i.e. generated by a CPG model) is not necessary to a legged robot. Some researches have already agreed with this viewpoint [31, 32]. In addition, a torque generator with DFC has already been proposed to adjust actuation. The torque control system corresponds to the reflex, which is defined as joint torque generation based on sensory information in physiology.

6.2 Towards realization of running and walking in a single-legged robot

Full and Koditschek indicated that adjustments based on the CPG and reflexes are dominant in low- or medium-speed animal motion (e.g. walking) and the self-stabilization property of the musculoskeletal system is more important than adjustments by the neural system in high-speed motion (e.g. running) [15]. Based on this hypothesis, it is expected for a legged robot that the adjustments of the control system (corresponding to the neural system) plays an important role in walking and stabilizing the unsteady state (e.g. the transient state and adaptation to a rough terrain), and the self-stabilization properties of the mechanical system (corresponding to the musculoskeletal system) work in steady running. Motivated by the above-mentioned consideration, in this study the authors attempt to construct a single control method unifying the two schemes. At low and medium speeds, the rhythm generator can generate the adaptive motion pattern and the torque generation can realize the required energy accumulation, both by mutual entrainment. At high-speed running, the role of the rhythm generator becomes small but not because no external synchronization is performed. Locomotion is dominated by the mechanical properties (i.e. self-stability) and the torque generator only provides minimum compensation to confront the energy loss from friction and collisions.

The proposed control method provides an alternative for designing a legged robot capable of both running and walking. In addition, it is also significant that the simulation and experimental results of this study effectively verify those hypotheses in biology.

7 CONCLUSION

This paper has dealt with the design of a quadruped robot, suited to the demands of fast legged locomotion, and the control of this robot to achieve stable running. A simpler controller inspired by biological concepts has been proposed here to provide stable running on a flat terrain (i.e. running from standing to steady bounding) and to adapt to a low-level irregular terrain (i.e. running up a 2 cm height step). The *Rush* quadruped robot is designed to use only one sensory feedback from the contact sensor due to the fact that the simpler sensory information can be easily and accurately measured as compared with other measurements of state variables (e.g. running

speed, jumping height, and so on). Despite its simplicity and its limited sensory feedback in the prototype, the *Rush* quadruped robot is able to realize energy-efficient running by fully taking advantage of self-stabilization properties. Since the delayed feedback control has been introduced to the proposed control method, the controller performs a significant function where it mainly works for transient state and adaptation, but almost does not operate in the steady state without providing minimum energy compensation. The function can help to construct a legged robot unifying walking and running controls. Both simulations and experiments show the validity of this approach. Although a model system has been constructed to describe the physical behavior in simulation studies accurately, the error that exists between simulation and experimental parameters cannot fully be secluded. Such errors result in some relative departures of state variables, in particular torque output and energy consumption. However, the running locomotion of the *Rush* quadruped robot can still be stabilized through the influence of the proposed control method in the same way as in simulation. Even on a low-level irregular terrain, an identical adaptation also appears in both simulations and experiments. In fact, the main sources of error between simulations and experiments are the absence of accurate estimates of the ground reaction force, toe-ground friction, and viscoelasticity at each joint. Stabilization and adaptation described in this paper do not rely on an accurate physical model and complex sensory feedback. Moreover, these error complications are considered to be disturbances in the controller. Therefore, running of the quadruped robot can still autonomously converge to a certain fixed point.

To the best of the authors' knowledge, a few works emphasize autonomously and efficiently generating and stabilizing running on a flat or rough terrain although there are various researches of three-dimensional quadruped walking or running. In addition, this study has also addressed a very important subject that has not received much attention in the dynamically stable legged robot literatures: unifying walking and running in one robot. At present, the proposed control method can stabilize running on a flat terrain and adapt to low-level irregularity of the terrain, but it is inadequate when confronting the disturbance that regularly changes the energy of the system (e.g. running uphill or downhill). In simulations, an accessorial adaptation control that autonomously adjusts the desired leg angle relative to the body has been

successfully performed to maintain stable running up- and downhill. In order to realize the adaptation to slopes, even in real three-dimensional running, the *Rush* robot must rely on proprioceptive feedback from a rate gyro and inclination sensor. Fortunately, these hardware and control expandabilities had already been adequately considered when the authors started to design the *Rush* quadruped robot.

ACKNOWLEDGEMENTS

The authors would like to thank Yasuhiro Fukuoka and Toshiki Masuda for their assistance in this work. The work has been partially supported by a Grant-in-Aid for Scientific Research on Priority Areas on 'Emergence of adaptive motor function through interaction between body, brain and environment' from the Japanese Ministry of Education, Culture, Sports, Science and Technology. Zu Guang Zhang's work has been supported by the Aid-Fund for Encouraging Research at Tokyo University of Science.

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APPENDIX

Notation

f	foreleg
h	hindleg
K_d	differential gain of PD control
$K_{DF \cdot T}$	period gain of DFC
$K_{DF \cdot \tau}$	torque gain of DFC
K_p	proportional gain of PD control
l	legs (i.e. f or h)
n	number of steps
$T_l[n]$	cyclic period of leg l in the n th step
γ_l	leg angle relative to the body in the swing phase
$\dot{\gamma}_l$	leg angle velocity relative to the body in the swing phase
γ_l^{td}	desired leg angle relative to the body
τ_l	torque output of the hip joint of leg l

$\tau_l^{\text{st}}[n]$	constant torque of leg l in the stance phase	ψ_l	initial phase of leg l
ϕ_l	phase of leg l	$\omega_l[n]$	angular frequency of leg l in the n th step
ϕ_{0l}	phase offset of leg l		