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Towards Realization of Adaptive Running of a Quadruped Robot Using Delayed Feedback Control

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***Abstract*— In this paper we present the system design and analysis of a quadruped robot, $Rush$, that we have constructed to study autonomous and efficient running on flat and rough terrain. The $Rush$ robot is a compact, kneed, four legged machine with only one actuator per compliant leg. We have proposed a novel control strategy for the quadruped robot 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 our previous reports. Here, the results obtained from experiments with $Rush$ are found to agree with the simulation results. The work reported in this paper may help improve our understanding of energy efficient running locomotion and the simple control required to autonomously stabilize it on flat or rough terrain.**

I. INTRODUCTION

Motivated by Raibert's success [1], many studies have been conducted on running of legged robots. Since the 1990s, there has been progress on the stability analysis [2] and the development [3] of one-legged hopping. By referring to the mobility of four-legged mammals, various control strategies for quadruped running have been explored in simulation studies [4]–[6] and experiments [7]–[9]. In addition, autonomous hexapod robots with high-speed mobility on irregular terrain have been recently developed [10], [11].

In general, the stabilization of running can be achieved when each state variable of running converges at a fixed point on the $Poincaré$ map. Seyfarth et al. took advantage of the model called Spring-Loaded Inverted Pendulum (SLIP) to explain that running can continue without more complex control if the touchdown angle is set at a desired value [12]. Such a dynamic property is called "self-stabilization." In fact, the self-stabilization property provides a simple and rational explanation for the stability of monopod hopping [13]–[15], and quadruped [6], [9], [16] and hexapod [11] running. Nevertheless, additional control methods using sensor information are still essential to realize the stable running of a quadruped robot on more irregular terrain.

To date, a number of studies of legged robots only focus on the realization of various gaits and balance. To the best of our knowledge, few researchers emphasize autonomously and efficiently generating and stabilizing running on flat or rough terrain. Our research aims at constructing an autonomous quadruped running robot, called $Rush$. The goals of the study are two-fold: (1)to realize steady running with good energy efficiency, and (2)to autonomously suppress such disturbances as irregularities of terrain. In our previous reports [17], we have proposed a novel control strategy, consisting of a rhythm generator and a torque generator with Delayed Feedback Control(DFC), to accomplish this. Several simulation studies have been already performed to confirm the validity of the control strategy. Our simulations 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 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, we mainly present the design considerations and hardware components of the $Rush$ robot. Utilizing the designed quadruped robot, we carry out experiments in which the robot runs from standing to steady bounding on flat terrain. Moreover, we have recently accomplished a new experiment with the $Rush$ robot where it succeeded in running up a 2cm-height step. These experimental results agree well with the corresponding simulation results reported in our previous paper [17]. Finally, we finish the report with a description of future work and a short conclusion. It should be noted that a more detailed publication will be available in the future.

II. DESIGN CONSIDERATIONS

We considered the following characteristics before designing and manufacturing the $Rush$ robot:

- In order to decrease the impact force and confront collision during rebound with the ground, the robot must be designed as a light and sturdy mechanism. This reduces the need for frequent repair.
- To have high power actuators and minimal leg inertia. It provides quick motion and response when the robot runs.
- To have compliant legs. It provides efficient energy exchange during cyclic running period and applies passive dynamics to running control.
- To have good amplification of torque. In general, the larger amplification of torque is required to provide

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enough power. So, it is reasonable to use a larger gear reduction ratio. But, immoderate reduction ratio will produce needless self-locking of the joint so as to consume more energy to drive the joint.

- To have an adjusting feature for leg length and leg compliance during one cyclic period of running. As a platform for the research of robot control and adaptation, it will help to investigating various forms if the physical parameters of the robot can be easily adjusted.
- To be untethered. We aim at having a compact and self-contained robot that contains the onboard locomotion controller and mobile power source.
- To be controlled in real-time and to emphasize rapid code development by taking advantage of user-friendly software tools.
- To allow future addition and development of actuators and sensors. Although the current design of the quadruped robot emphasizes simplified sensory feedback and active joints, it is still important to increase sensor feedback(e.g., gyro sensor for measuring the angular acceleration of the body) and actuators so that the robot is capable of adapting to more irregular terrain.

In our current quadruped robot *Rush*, all these desired characteristics have been accomplished, except the untethered feature and adjustable leg compliance.

III. HARDWARE

Fig. 1 shows the *Rush* robot we used to study running. Its main parts are a rigid body and four compliant legs, connected by rotary hip joints. The body consists of a platform that carries actuators, transmission devices and computer interface electronics. The total weight of the robot is 4.3 kg. The length and width of the body are 30 cm and 20 cm, respectively. The height of a leg is 20 cm when the robot stands. Detailed values of physical parameters are listed in Table I

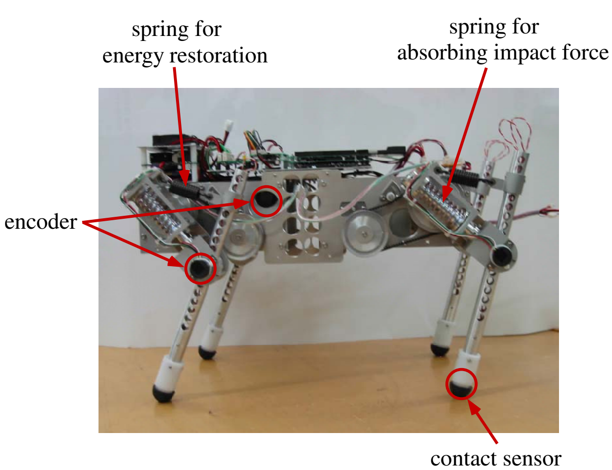

Fig. 1. A quadruped running robot *Rush*. The size is 30 cm in length and 20 cm in width. The height of the leg is 20 cm. The total weight is 4.3 kg.

TABLE I
THE PHYSICAL PARAMETER VALUES OF THE DESIGNED ROBOT *Rush*

Parameter	Value	Unit
Upper leg length(uncompress)	0.08	m
Lower leg length	0.15	m
Motor power	27.5	W
Motor torque constant	70.4	mNm/A
Motor armature constant	12.5	Ω
Spring constant(knee joint)	20	kN/m
Direct-acting spring constant	7.4	kN/m

The design of *Rush* emphasizes simplified sensory feedback. Thus, only encoders and contact sensors are attached to each joint and toe, respectively, so as to measure the rotary angles of joints and the stance phase period. Although this sensor configuration is sufficient for controlling and stabilizing quadruped running described in this paper, we 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 rougher terrain (e.g., slope).

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 necessary for a running robot to be designed with compliant legs and a compact controller.

A. Leg Design Description

As illustrated in Fig. 2, the leg consists of an upper and a lower part. Both parts are considered to be a chain of two rigid segments with a 20 kN/m spring and a passive knee joint. The toe is narrow, using a hemispheric piece of hard rubber and providing a good approximation to a point of support. In the upper part, a special mechanism referred to as direct-acting spring device is mounted to absorb impact force, so the impact damage acting on the shaft of each joint during rebound with the ground can be reduced. Each hip is actuated by a 27.5 Watt DC motor, a three-stage planetary gearbox, and a belt and pulley pair, with a 19:1

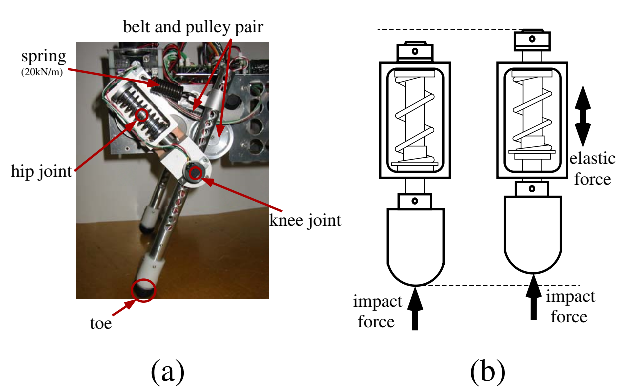

Fig. 2. The design of a compliant leg. It has two main parts, an upper and a lower part, connected via a spring (20 kN/m): (a) photograph, (b) a direct-acting spring device is capable of absorbing impact force during each stance phase.

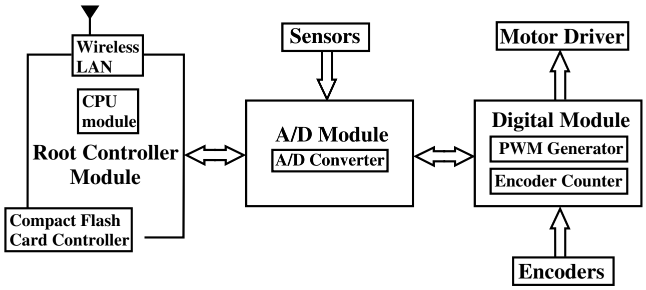

Fig. 3. The computer system includes a compact controller equipped with wireless LAN and a high-speed serial bus that connects several serial I/O nodes in cascade.

reduction ratio, providing a good amplification of the torque and compliance of the joints.

B. Controller Description

Since a robot such as *Rush* has to fulfill 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 included in the body of the robot, so a light and compact device is also important. Therefore, we employ a specially made computer system for robot control. The computer system called TITech-Wire, which includes a compact controller equipped with wireless LAN and a high-speed serial bus that connects several serial I/O nodes in cascading fashion. Through such a serial bus, the add-on analogue and digital I/O interfaces can be easily implemented. The TITech-Wire installed in *Rush* contains three major modules (i.e., root control module, A/D module and digital module), as shown in Fig. 3. The root control module consists of a CPU module (AMD Elan520 133 MHz), a PC card controller driving the wireless LAN card, and a compact flash card controller. Analogue signals from various sensors are interfaced throughout the A/D module. The digital module generates PWM signals to control rotation of motors, and counts the angular information from each encoder attached to each joint. In order to obtain real-time control, we 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 *Rush* control program.

IV. CONTROL

The control of locomotion of the robot is based on coupled-dynamics-based motion generation (see Fig. 4). Such control concept has three benefits, as listed here:

1) They avoid serious problems in robotics such as modeling of mechanical system and environment, conflict between planned motion and actual motion and so on.
2) They require only simple command signals to produce complex coordinated multi-dimensional output signals.
3) They easily incorporate sensor feedback and take mechanical perturbations into account.

It should be mentioned that designing and constructing a control system is the most important subject in coupled-dynamics-based motion generation while taking the dynamics of a mechanical system and its interaction with the environment into account. In general, the issue of the realization of adaptive running is classified as the generation of the gait and the energy input. Therefore, we design the control system, consisting of a rhythm generator and a torque generator, to realize the generation of the gait and the energy input, respectively.

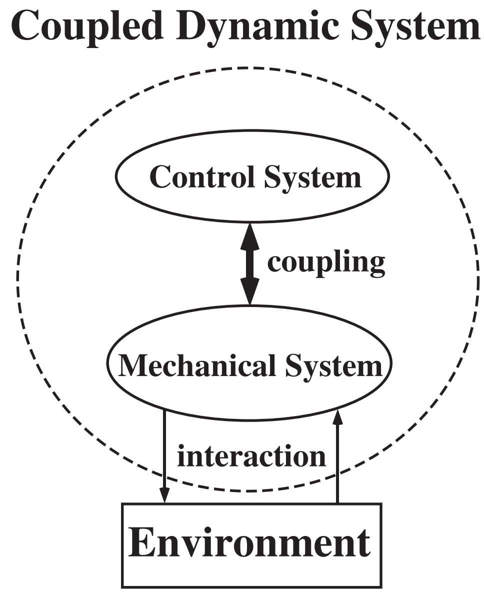

Fig. 4. Locomotion generation and adaptation are emergently induced by the coupled dynamics of a control system and a mechanical system by interacting with the environment.

Furthermore, Poulakakis et al. indicated that the self-stabilization property of the mechanical system can facilitate the design of more robust controllers for stable legged locomotion [6]. Thus, we have also studied quasi-passive running locomotion, with a conservative sagittal quadruped model, to verify the self-stabilization properties of robots such as *Rush* [16]. In our control strategy, we consider that friction and collision in an actual system are only disturbances around the quasi-passive running, and the proposed control system is only used to suppress these disturbances.

We consider the following discrete dynamic system,

$$\boldsymbol{x}[n+1] = \boldsymbol{\mathcal{F}}(\boldsymbol{x}[n], \boldsymbol{u}[n]) \quad (1)$$

$$\boldsymbol{y}[n] = \boldsymbol{\mathcal{G}}(\boldsymbol{x}[n]) \quad (2)$$

where $\boldsymbol{x}$, $\boldsymbol{u}$ and $\boldsymbol{y}$ are state variables, control inputs and measured state by sensors, respectively. The unstable fixed point $\boldsymbol{x}^*$ is stabilized by the following control strategy: DFC.

$$\boldsymbol{u}[n] = \boldsymbol{\mathcal{K}}(\boldsymbol{y}[n] - \boldsymbol{y}[n-1]) \quad (3)$$

It should be noted that the stabilization can be realized without specifying any desired values (e.g., the desired energy state) in DFC. In addition, by calculating adjusting torque based on the difference of the energy state, Osuka et al. asymptotically stabilized a planar biped walking on a

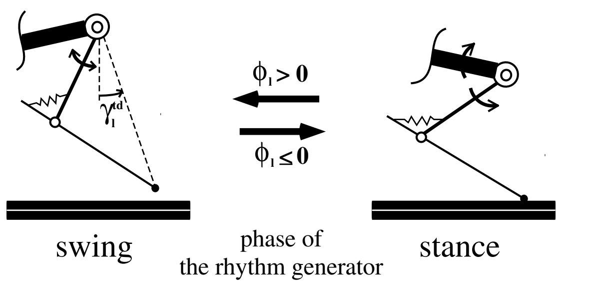

Fig. 5. Switching of the hip joint controller according to the output phase: ϕ_l of the rhythm generator.

downhill slope around the fixed point of passive dynamic walking in their simulations [18].

We might be able to calculate the system energy as $\boldsymbol{y}$ in DFC by using data measured by sensors located in the robot. For instance, when measuring the jump height and forward speed in a running robot through an acceleration sensor. But, we have to solve issues such as integration error, noise and drift. Therefore, it becomes difficult to realize the appropriate feedback process with the system energy calculated from imprecise state values.

On the other hand, Cham et al. adjusted the stride period by measuring ground contact information and realized high-speed running of a hexapod robot over irregular terrain [11]. Motivated by their work, we also use the stance phase period, with better accuracy[1], as $\boldsymbol{y}$ because it is difficult to accurately calculate the energy of the running as described above.

A. Rhythm Generator

We define the phase of each leg in the n^{th} step ϕ_l as expressed by Eq.(4). The timing for each leg to switch between the stance and swing phase is: $\phi_l > 0$:swing phase, $\phi_l \leq 0$:stance phase. (Fig. 5)

$$\phi_l = \sin(\omega_l[n]t + \psi_l) + \phi_{0l}, \quad \omega_l[n] = \frac{2\pi}{T_l[n]} \tag{4}$$

where $T_l[n]$ and $\omega_l[n]$ are the cyclic period and the angular frequency of the leg l in the n^{th} step, respectively. The initial phase ψ_l is defined for the generation of the gait[2]. The offset ϕ_{0l} determines the duty factor. $T_l[n]$ is calculated by using the DFC method described in Section *IV-C*.

B. Torque Generator

Depending on the leg phase ϕ_l generated by the rhythm generator, the following control actions are assigned as shown in Fig. 5.

- In the swing phase ($\phi_l > 0$), the PD control expressed by Eq.(5) is performed.

$$\tau_l(t) = -K_p(\gamma_l - \gamma_l^{td}) - K_d\dot{\gamma}_l \tag{5}$$

- In the stance phase ($\phi_l \leq 0$), constant torque $\tau_l^{st}[n]$ of the hip joint in each leg is output, as expressed by Eq.(6).

$$\tau_l(t) = \tau_l^{st}[n] \tag{6}$$

In the control action of the swing phase, γ_l^{td} is the touchdown angle with respect to a specific fixed point. 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 *IV-C* determines $\tau_l^{st}[n]$.

C. DFC with Stance Phase Period

We use the following definitions to express $\boldsymbol{x}$ and $\boldsymbol{y}$ in the discrete dynamical system expressed by Eq.(1) and Eq.(2).

$$\boldsymbol{x}[n] = [T_f[n], T_h[n], \tau_f[n], \tau_h[n]]^T \tag{7}$$

$$\boldsymbol{y}[n] = [t_f^{st}[n], t_h^{st}[n]]^T \tag{8}$$

where $t_l^{st}[n]$ represents the n^{th} stance phase period measured by a contact sensor. As described in the above-mentioned section, we use this stance phase period to propose the following DFC methods.

$$T_l[n+1] = T_l[n] - K_{DF\cdot T}(t_l^{st}[n] - t_l^{st}[n-1]) \tag{9}$$

$$\tau_l^{st}[n+1] = \tau_l^{st}[n] - \delta(l)K_{DF\cdot\tau}(t_l^{st}[n] - t_l^{st}[n-1]) \tag{10}$$

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

where $K_{DF\cdot T}$ and $K_{DF\cdot\tau}$ are DFC gains. Eq.(9) and Eq.(10) correspond to Eq.(1) and Eq.(3), and are used to calculate the cyclic period of the leg phase and hip joint torque of the next stance phase, respectively.

$K_{DF\cdot T}$ and $K_{DF\cdot\tau}$ are determined by trial and error in experiments outlined in Section **V** since the map $\boldsymbol{\mathcal{G}}$ in Eq.(2) is complex and it is difficult to analytically seek the DFC gains that enable state variables to converge at a fixed point.

V. RESULT

To validate the simulation results stated in our previous reports [17], we utilize the quadruped robot *Rush* presented in Section **III** to implement an experiment in which *Rush* runs from standing to a steady bounding state on flat terrain. In order to generate the bounding gait, we 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 Eq.(9) and Eq.(10). The initial values of $T_h[0]$ and $\tau_h[0]$ are much larger than those in the steady state for providing the sufficient kinetic energy during the first stance phase period of hind legs. The parameter values in the control strategy for these experiments are listed in Table II

Fig. 6 presents snapshots of *Rush*'s bounding locomotion on flat terrain with the proposed control strategy. As shown in Fig. 7(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 since about 4.5 s. Fig. 7(right) illustrates that running period $T_l[n]$ generated

[1]The sampling time of the control loop permits an error margin of about 1 (ms), for example.

[2]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.

Fig. 6. Snapshots of Rush running in the bounding gait.

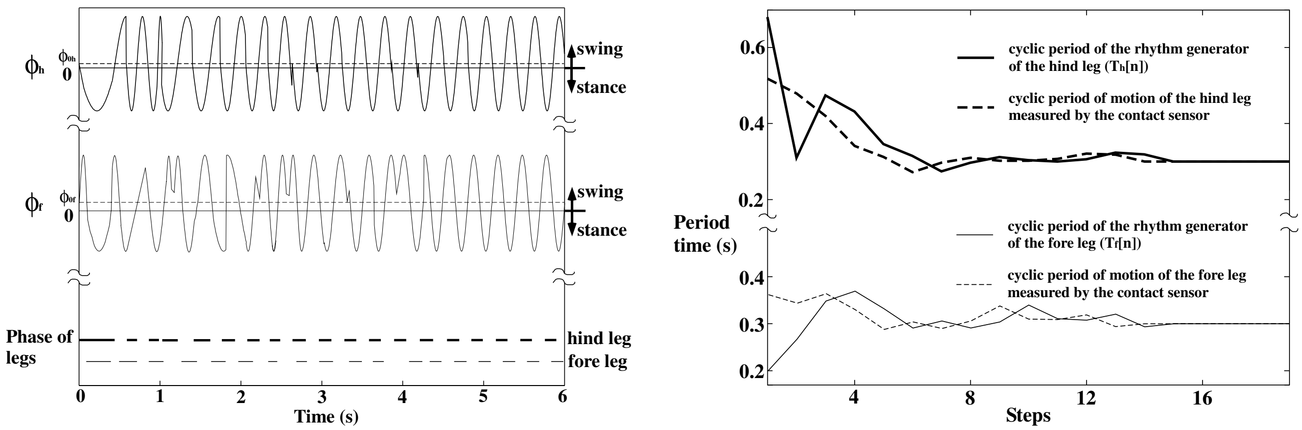

Fig. 7. The experimental results of DFC in the transition from standing to steady bounding. The output phase of the rhythm generator and the phase of the leg measured by the contact sensors are shown in the left graph. The cyclic period of the rhythm generator and the cyclic period of leg motion measured by the contact sensor are shown in the right graph. The experimental running period is approximately $0.30s$.

TABLE II
THE PARAMETER VALUES OF THE CONTROLLER USED IN EXPERIMENTS.

Parameter	Value	Parameter	Value
ψ_f	0	ψ_h	π
ϕ_{0f}	0.16	ϕ_{0h}	0.09
γ_f^{td}(rad)	0.524	γ_h^{td}(rad)	0.838
$K_{DF\cdot T}$	0.12	$K_{DF\cdot \tau}$	6.8
K_p(N·m/rad)	10	K_d(N·ms/rad)	0.02

by a rhythm generator accords with that measured through a contact sensor after the 15^{th} step. Note that the experimental results, especially the transitional patterns of the cyclic period of rhythm generators and legs, agree with the results in simulation shown in [17].

Fig. 8 shows test results of the torque generators implemented in $Rush$ running on flat terrain. The top graph shows output values during the whole bounding period. The bottom graph shows constant torque of the hip joints of fore and hind legs in each stance phase. Note from the bottom graph that, although the constant torque during the initial stance phase period is set at a large value (i.e., -1.80 Nm and 1.80 Nm), the steady-state torque still converges to a minor value (i.e., -0.85 Nm and 0.93 Nm) since the DFC method in torque generators works effectively. The convergence value of torque is higher than the value in simulation reported in [17] and results in somewhat higher energy consumption. However, in consideration of modeling errors of collision and friction, the somewhat higher energy consumption is still considered to have good energy efficiency. It is important to mention that such torque adjustment in the process of state transition has not been reported in the legged robot literature to date.

As a result, the experimental running period is approximately 0.30 s, average forward speed is 0.9 m/s, and the maximum height of the toes (i.e., clearance) in the fore and hind legs are respectively 5 cm and 4.5 cm. Note that we use a hand-held chronometer for forward speed measurement. In addition, the jump-height and clearances are measured with visual observation in the video of the experiments. Although such measurements are not very accurate, we may still use these results because the proposed control strategy for $Rush$ doesn't directly use these measured state variables as feedback.

VI. CONCLUSIONS AND FUTURE WORK

This paper presented the first result in the research program that aims at developing $Rush$, a quadruped robot capable of autonomously and efficiently running on flat or rough terrain. The design considerations and the $Rush$ hardware were described in detail. A novel control strategy was proposed in consideration of several engineering limitations on sensor feedback. In the control strategy, a rhythm generator and a torque generator were used to construct a coupled dynamic system. The states of both generators are modulated by Delayed Feedback Control (DFC) using

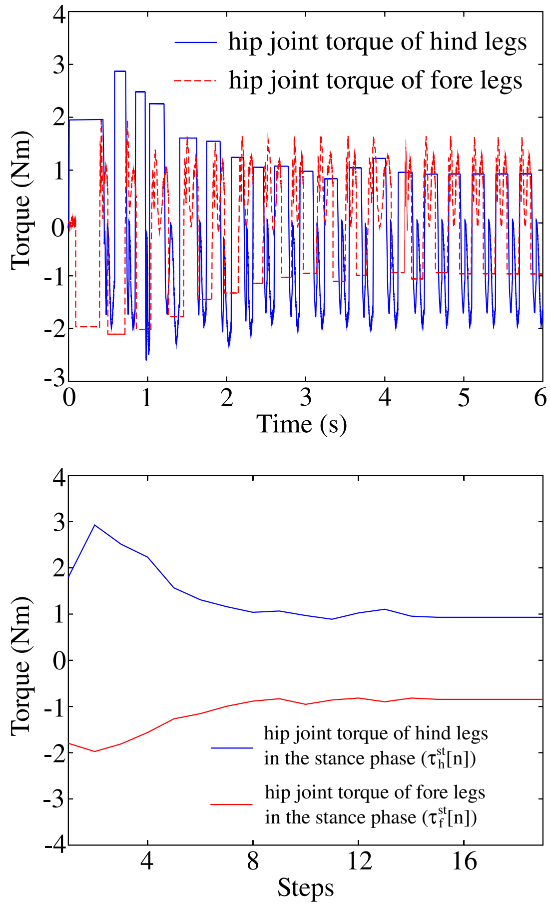

Fig. 8. Torque of the hip joints in fore and hind legs when *Rush* is running on flat terrain from standing to steady bounding. The top graph shows output values during whole bounding period. The bottom graph shows constant torque of hip joints in each stance phase.

a stance phase period measured by contact sensors. The simulation results described in our previous reports [17] were partially confirmed in experiments using the *Rush* quadruped robot.

Finally, the proposed control strategy has the ability to suppress the disturbances which cause temporary energy change relative to the touchdown plane. Recently, the ability in suppressing such low-level disturbances has been demonstrated by an experiment in which the *Rush* quadruped robot succeeded in running up a 2cm-height step without aidance of other extended control methods (watch the accompanying movie). To the best of our knowledge, a control strategy capable of resulting in the transition from standing to steady running and stabilization in running up a small step is first mounted at an actual quadruped running robot.

Although the proposed control strategy is capable of stabilizing running on flat terrain and adapting to low-level irregularity of terrain, it is still inadequate when confronting disturbances that regularly change the energy of the system(e.g., running uphill or downhill). Therefore, further study in autonomous adaptation on high-level irregularity of terrain is necessary.

VII. ACKNOWLEDGMENTS

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