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BIPED BALANCE CONTROL BASED ON THE FEEDBACK OF GROUND REACTION FORCES WITH GRAVITY COMPENSATION

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ABSTRACT
We have proposed the CoP, i.e, ZMP feedback control for the weight shift in biped double support as well as balance maintenance under unknown stationary environments. The stability of the biped balance is well discussed there, but the response of the control law is not so fast in actual application. To improve this, we introduce a gravity compensation term to cancel the gravity effect immediately at the start of the control. The stationary posture with a large stability margin is obtained even under unknown external force, and its stability is ensured based on a simple inverted-pendulum model. The effect of this improved control is examined by applying it to the biped walk on the slope. A biped robot showed a walk without changing or adjusting the control law even on the upward and downward floors.

INTRODUCTION
A standard method of realizing biped walk is a control scheme based on the ZMP (Zero Moment Point)[1]. The motion represented by the positional trajectory of joint angles or the CoM of some links is planned at first so that the ZMP calculated from the gravitational and internal forces remain inside the support polygon, the convex hull including all the contact points to the ground. Then, the positional feedback control is applied to track this trajectory. This ensures no turnovers of the robot in the sense that the foot segment remains stationary and does not rotate around its edge.

This method is quite powerful and effective but does not monitor the actual ZMP position; it is not always within the support polygon if parameters in the robot environment, such as the gradient of the ground, have varied.

To adapt to environmental change, the online planning of the center of mass (CoM) trajectory [2] is considered in combination with the ZMP criterion. By performing a robot demonstration and mathematical analysis, some studies aim to ensure the stability of the control result using return (Poincare) maps [3], and nonlinear dynamics [4].

To deal with the environmental variation, additional information should be added to the control law. For example, we have been focusing on the ground reaction forces. Actually, the ZMP is equivalent to the center of pressure (CoP) of ground reaction forces [5], implying that ground reaction forces would contain effective information regarding balance. Our idea for adapting to the environmental changes is that although the joints of CoM trajectories vary with the slope angles, the trajectory of the CoP position does not change during locomotion, especially in the lateral direction, as illustrated in Fig. 1. Because of this invariance, we select the CoP trajectory as the control reference.

Following this idea, we proposed a balance control law demonstrating adaptive balance maintenance during the static standing [6] as well as the in-place stepping [7]. However, the effect of feedback of CoP position does not show the fast response because it works as the integral of the error of CoP positions. To improve it at the moment of when a new control phase starts, we here try introducing the gravity compensation that works fast as feedforward manner. In the following sections, we will discuss the stability of the balance in case that this new control law is utilized. Then, we apply it to the biped locomotion of actual robot we designed.

ORIGINAL CONTROL METHOD
We begin with an analysis of balance control by introducing the feedback of ground reaction forces based on a simplified model. Figure 2 shows an inverted-pendulum model in the two-

dimensional space. The two segments, a body segment and foot segment, are connected at the ankle joint located at the same height as the ground. The foot segment is symmetrical in the anterior-posterior direction, while the ankle joint is situated at the center of this segment and makes contact with the ground at both ends. We can detect the vertical component of the ground reaction forces, F_H and F_T, at these contact points as well as the angular deviation θ and velocity $\dot{\theta}$ of the ankle joint. F_X and F_Y denote an unknown external force being exerted on the body segment; this can represent actions by the

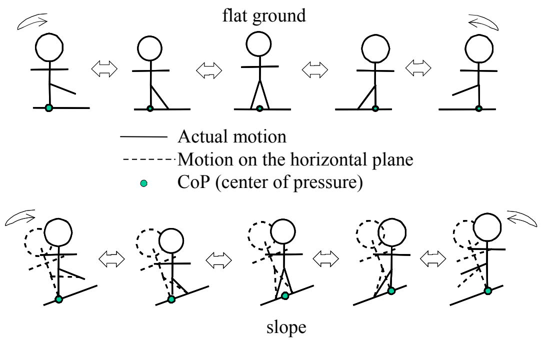

Figure 1: CoP trajectory on the flat and sloped ground.

environment such as the gravitational effect on the slope. In the following analysis, they are assumed to be constant though unknown.

If F_H and F_T takes the same value, the CoP, in other words ZMP, is situated at the center of the foot segment. Thus, we set the objective of the control law as the stabilization of the situation of $F_H - F_T = 0$.

In our previous paper [6], we have already proposed such a control law for ankle joint torque τ:

$$\tau = -K_d\dot{\theta} + K_p(\theta_d - \theta) + K_f\int(F_H - F_T)dt \qquad (1)$$

Here, the parameters K_d, K_p, and K_f are the feedback gains.

According to this control law, the posture of the inverted pendulum model surely changes with external forces so as to make F_H and F_T equal. This effect actually comes from the third term but does not work instantly, because it works with the integratal of the error, $F_H - F_T$. Thus, when it is applied to the balance control, it sometimes delays the compensation of the action of external force containing the gravitational effect.

AN IMPROVED CONTROL METHOD

Control law with gravity compensation

To improve this, we now propose a new control law:

$$\tau = -K_d\dot{\theta} + K_p(\theta_d - \theta) + K_f\int(F_H - F_T)dt - MgL\sin\theta \quad (2)$$

This is different in the existence of the fourth gravity compensation term: it works fast in a feedforward manner.

Dynamics

Here we assume that the foot segment shows no movement. Then the motion of the body segment is described as follows:

$$I\ddot{\theta} = MLg\sin\theta + F_x L\cos\theta - F_y L\sin\theta + \tau, \qquad (3)$$

where M is the mass of the body segment, g is the gravitational acceleration, and L is the distance of the CoM of the body segment from the ankle joint, I is the inertial moment of the body segment around the ankle joint.

The internal force is exerted between two segments, whose horizontal and vertical components, f_x and f_y, are described as follows:

$$f_x = ML\ddot{\theta}\cos\theta - ML\dot{\theta}^2\sin\theta - F_x \qquad (4)$$

$$f_y = -ML\ddot{\theta}\sin\theta - ML\dot{\theta}^2\cos\theta + Mg - F_y \qquad (5)$$

Using this f_y, the ground reaction force, F_H and F_T, are given by

$$F_T = -\frac{1}{2\ell}\cdot\tau + \frac{1}{2}mg + \frac{1}{2}f_y \qquad (6)$$

$$F_H = \frac{1}{2\ell}\cdot\tau + \frac{1}{2}mg + \frac{1}{2}f_y \qquad (7)$$

Here m is the mass of the foot segment, and ℓ is the length from the ankle joint to the end of the foot segment.

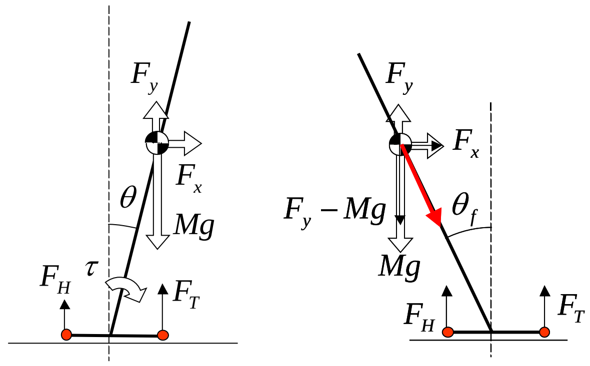

Fig. 2: Two link model for biped standing control.

From Eq. (6) and Eq. (7), we can obtain the following relation:

$$F_H - F_T = \frac{1}{\ell}\cdot\tau \qquad (8)$$

Stationary state

For the motion equation of the body segment, Eq. (3), and the force balance equation at the body segment, Eq. (8), we apply the control law, Eq. (2). First, we analyze the stationary state in this case. To clarify the calculation, we introduce a new state variable τ_f defined as

$$\tau_f = \int(F_H - F_T)dt \qquad (9)$$

Substituting Eq. (2) and Eq. (9) into Eq. (3), we obtain

$$I\ddot{\theta} = F_x L\cos\theta - F_y L\sin\theta + \\ -K_d\dot{\theta} + K_p(\theta_d - \theta) + K_f\tau_f \qquad (10)$$

On the other hand, differentiating Eq. (9) and then replacing with Eq. (8) and Eq. (3), we get

$$\dot{\tau}_f = \frac{1}{\ell}(-K_d\dot{\theta} + K_p(\theta_d - \theta) + K_f\tau_f - MgL\sin\theta) \quad (11)$$

The equilibrium point $(\bar{\theta}, \bar{\tau}_f)$ of the two dynamical equations Eq. (10) and Eq. (11) are given as the solution of the algebraic equations that are obtained by substituting $\ddot{\theta} = \dot{\theta} = 0$ and $\dot{\tau}_f = 0$:

$$F_x L\cos\bar{\theta} - F_y L\sin\bar{\theta} + K_p(\theta_d - \bar{\theta}) + K_f\bar{\tau}_f = 0 \quad (12)$$

$$\frac{1}{\ell}(K_p(\theta_d - \bar{\theta}) + K_f\bar{\tau}_f - MgL\sin\bar{\theta}) = 0 \quad (13)$$

The solutions are given as follows:

$$(\bar{\theta}, \bar{\tau}_f) = (\theta_f, \frac{1}{K_f}(K_p(\theta_f - \theta_d) + Mgl\sin\theta_f) \quad (14)$$

where, θ_f is an angle defined by

$$\tan\theta_f = -\frac{F_x}{Mg - F_y} \quad (15)$$

The posture of this stationary state is illustrated in the right of Fig. 2.

In this state, the moment generated by the gravity and external force are balanced around the ankle joint. Accordingly, the ankle joint torque can be zero, and is, thus, very effective from an energy consumption point of view. In addition, the CoP is kept at the center of the foot segment, which ensures good performance from the perspective of the stability of balance. Note that θ_f depends on the external force F_x, F_y, indicating that this stationary posture adaptively changes with external force.

Stability analysis

Next we discuss the stability of this stationary state. Putting $\theta_1 = \theta$ and $\theta_2 = \dot{\theta}$, and then linearizing the equations around the equilibrium point, we obtain

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\tau}_f \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -\frac{C_f + K_d}{I} & -\frac{K_d}{I} & \frac{K_f}{I} \\ -\frac{C_g + K_p}{\ell} & -\frac{K_d}{\ell} & -\frac{K_d}{\ell} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \tau_f \end{bmatrix} \quad (16)$$

Here,

$$C_f = F_x L\sin\theta_f + F_y L\cos\theta_f \quad (17)$$

$$C_g = MgL\cos\theta_f \quad (18)$$

The characteristic equation of this linear differential equation is

$$\lambda^3 + p_2\lambda^2 + p_1\lambda + p_0 = 0 \quad (19)$$

where

$$p_2 = \frac{K_d\ell - K_f I}{I\ell} \quad (20)$$

$$p_1 = \frac{K_p + C_f}{I} \quad (21)$$

$$p_0 = \frac{K_f(C_g - C_f)}{I\ell} \quad (22)$$

If we appropriately set the feedback gains K_d, K_p, and K_f to satisfy the Routh-Hurwitz criterion, $p_2 > 0$, $p_1 > 0$, $p_0 > 0$, and $p_2 p_1 > p_0$, we can stabilize this stationary state.

Extension as CoP feedback

Equation (2) can be rewritten as the CoP feedback. The CoP is a representative point when all the ground reaction forces are assumed to act at a single point [5], and the moment generated by the vertical component of all the ground reaction forces becomes zero. From this property, the position of the CoP is given as

$$P_{CoP} = \frac{F_T - F_H}{F_T + F_H}\ell \quad (23)$$

where the origin of the CoP position, P_{CoP}, is set at the center of the foot segment. The denominator $F_T + F_H$ corresponds to the total weight of the robot, which is considered to be constant for slow robot motion. By resetting the feedback gain K_f to contain this, Eq. (2) can be written as the feedback control of the CoP position to its desired value P_d:

$$\tau = -K_d\dot{\theta} + K_p(\theta_d - \theta) + K_f\int(P_{CoP} - P_d)dt - MgL\sin\theta \quad (24)$$

This control law is applied independent of the number of the contact points on the ground: Eq. (2) was restricted to the case of two contact points.

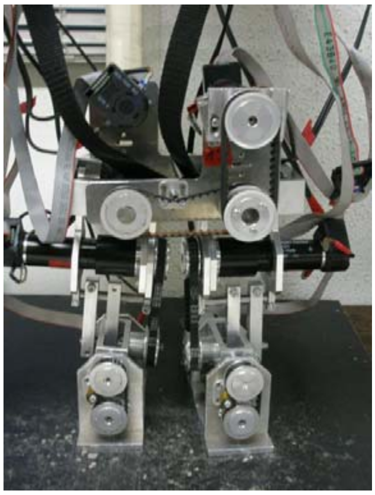

Figure 3: the robot used in the experiment.

ROBOT EXPERIMENTS

Experimental equipment

The goal of experiments is to confirm that the control law with feedback of the ground reaction forces, or CoP position, proposed here is effective, for example, on the slope.

Figure 3 shows the biped robot that we designed. It is 290 mm in height, 270 mm in width, and weighs 4.12 kg. Its feet are 160 mm long.

This robot has six motors: two motors are utilized for the ankle roll and pitch rotation in both sides. And the remaining two motors are for the coupled leg motions at the hip joints: A new hip joint structure was designed in which the one motor achieves alternative forward-backward swings of both legs symmetrical to the body position, while the other motor realizes the lateral sway motions with keeping the legs parallel to each other in the frontal view. The details are described in [8].

To detect the ground reaction forces, especially, their vertical component, load cells are attached at each corner of the square-shaped sole; a total of eight load cells are equipped. The number of strains is translated to the electric data, and they are acquired through an A/D converter board after amplification. In addition, the joint angles of the robot are detected using optical encoders that are included with each motor, and their pulses are counted by counter boards. These data are processed at a personal computer operated by real-time OS, and the motor commands corresponding to the joint torque are outputted from a D/A converter board. Motor drivers receive this command and supply the required electric current to a DC servo motor.

The horizontal ground, upward slope, and downward slope are tested. The angles are 5 degrees for both slopes. In each condition, the control law and its reference is set to be exactly same to demonstrate that our idea depicted in Fig. 1 works well.

Application to double support phase

In double support phase, the CoP moves from the bottom of one of the foot to another. It is exactly the case in Fig. 1: if the control is designed as the CoP tracking, it will be independent of the environmental variation such as the gradient of the ground.

From this point of view, we will introduce the control law Eq. (24), but the double support phase has a different structure of the single support phase illustrated in Fig. 2.: Actually, there is no single base joint whose output is regarded as τ in Eq. (24). In order to make Eq. (24) applicable, we will extend its formulation. Figure 4 shows a model of the double support phase based on our robot, which is represented as the five-link structure with the 2D motion.

First of all, we introduced a new coordinate ϕ denoting the lateral sway angle of the whole body in relation to the mid point of two feet: because the body movement in the double support phase has only one DoF, ϕ will be determined uniquely from the posture in double support phase. For the small deviation of this ϕ, we can calculate the deviation of the each joint angle, actually two hips and two ankles; which is written as

$$\Delta\Theta = \mathbf{J}(\Theta)\cdot\Delta\phi \tag{25}$$

where $\Theta \in R^4$ contains two hip and two ankle joint angles, $\mathbf{J}(\Theta) \in R^{4\times 1}$ is a Jacobian matrix relating the deviation of Θ and ϕ. Now, we define the generalized force τ_ϕ in the coordinate of ϕ using Eq. (24), and then distribute this generalization force to each joint torque, $\boldsymbol{\tau}$, using the following relation,

$$\tau_\phi = \mathbf{J}^{\mathrm{T}}(\Theta)\cdot\boldsymbol{\tau} \tag{26}$$

In this joint torque computation, we should use a generalized inverse matrix of $\mathbf{J}^{\mathrm{T}}(\Theta)$.

Actual control

Single support phase

In the single support phase, the CoP position is almost constant. Accordingly, the balance in the single support phase will be maintained by using the control law Eq. (2) or Eq. (24) with the constant desired position P_d. In this case, it should be assumed that the external force includes the inertial force produced by walking such as the leg swings or the movements of the body segment.

In the actual experiments here, the control law Eq. (2) was applied to the ankle joint for the supporting leg in the single support phase. For the two hip joints, the trajectory tracking control, which is the PD control without the gravitational compensation in the joint space, was adopted to generate the stepping motion. To promote the landing of the swing leg, the ankle joint of the supporting leg is used to slant the body to the swinging-leg side in the last part of the single support phase.

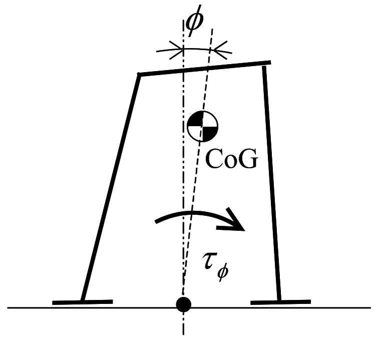

Figure 4: biped model in double support phase

Double support phase

The double support phase is accompanied by the shift of the CoP: the CoP position clearly moves from beneath the support leg in the previous single support phase to the other. This kind of CoP movement is realized by using the desired trajectory of CoP, $P_d = P_d(t)$, setting the desired position as time-variant. For this P_d, the control law Eq. (24)-(26) is introduced for the double support phase.

The motion of the body has only one DoF. Thus, in the experiments, we controlled the body motion only in the lateral plane: sagittal motion is produced as the result of the lateral motion control. We selected lateral control because the traveling distance in the lateral direction is longer than that in the sagittal direction owing to the short stride gait of kneeless legs. Accordingly, the motor that acts for the sagittal plane motion was made to give zero output during the double support phase to follow the lateral motion. ϕ is defined as the sway angle in the frontal view, in which the leg is always kept parallel.

The reference trajectory P_d should be define to induce the CoP shift by connecting the current CoP position and the desired one. For the simplicity of the motion design, we gave it with the 5 order polynomial, being continuous in its second derivative, that connects the CoP position at the start of the double support phase and center of the foot in front within the lateral plane.

Siwching between single and double support phase

In the double support phase, the monitored CoP position reaching the threshold is the trigger to change the control law for the single support phase. In the single support phase, the ground reaction force from the swinging leg is utilized to switch the control law: when it then takes nonzero values, the double support phase starts. This switching rule, which is based on the ground reaction forces (and not the joint angles), allows the robot to adapt to environmental changes.

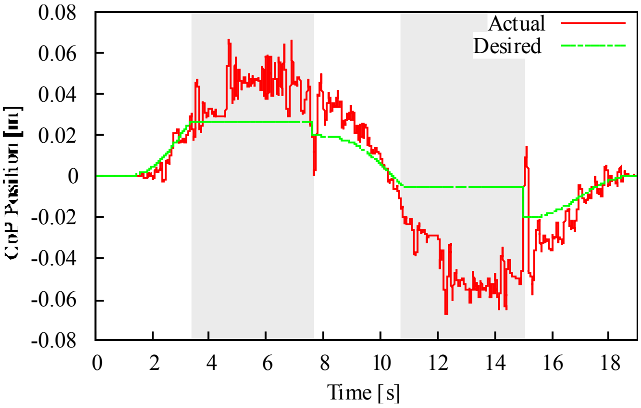

Figure 5: CoP trajectory in double support phase (unshaded area) with its desired trajectory.

Experimental result

The first experiment was conducted on the flat floor. The feature of this control law is found at the CoP tracking control in the double support phase. Thus, the time course of the CoP position is plotted in Fig. 5 with its desired one. In the unshaded area, we can observe that the CoP is tracking to its desired values though some delays still exist. (The shaded area, single support phase, did not adopt the same CoP tracking control. Thus the results should not evaluate by this graph.)

Next, we tried the walk on the upward and downward slopes. On the slope with unknown gradient, we cannot set the correct gravity compensation term in single support phase control since the exact effect of the gravity depends on the slope angle. Therefore, we replaced this term with $Mg \cdot P_{CoP}$: This exactly represents the moment caused by the gravity even on the slope; thus, the modified control can also compensate the gravity effect in the feedforward manner.

However, the robot still sometimes fell over because of high-frequency noise in the load cell signals. Introducing the integral operation as the low-pass filter, we finally realized that the biped robot walks on slopes. The photos of the walking on the slope are shown in Fig. 6. It should be noted that the biped

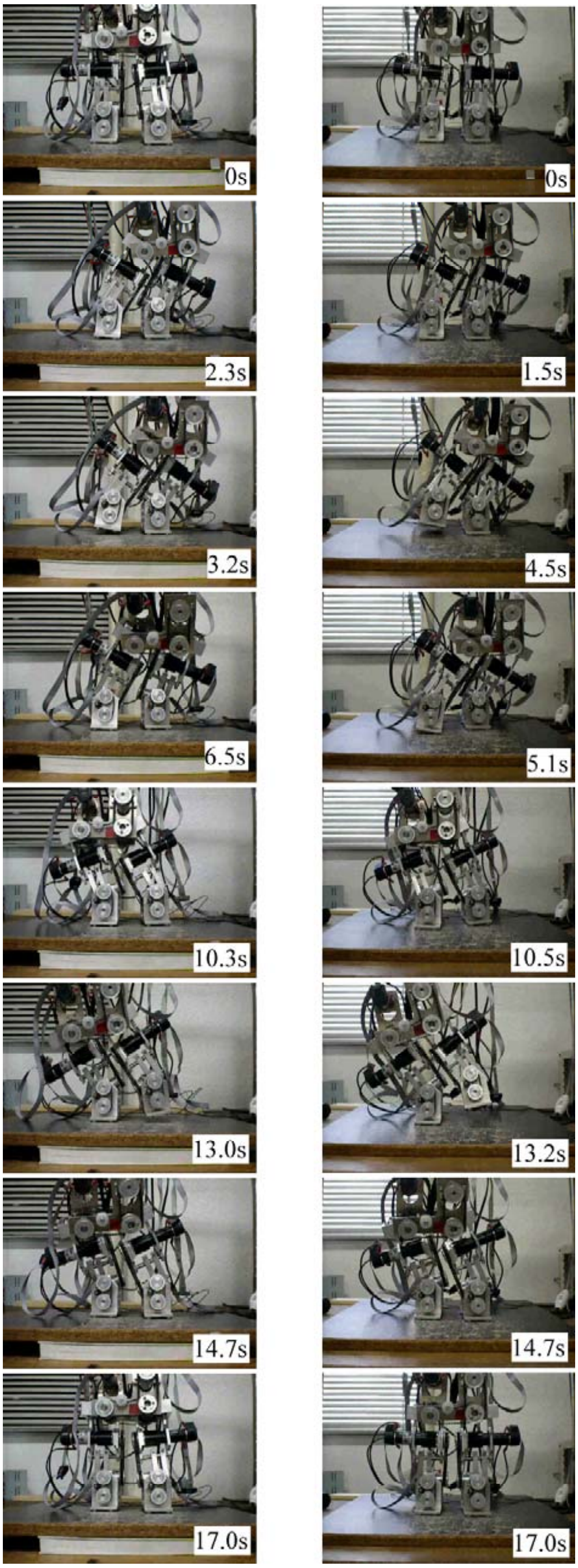

Figure 6: Biped experiments on upward (left) and downward (right) slope.

walks on the slope had not succeeded before the gravitational compensation was introduced.

CONCLUSIONS

As the adaptability of biped walk, we dealt with the change of the ground gradient. The target motion of the robot was selected in the realization of straight walking on previously unknown flat slopes. To achieve adaptive walking on slopes, the feedback of the ground reaction forces, or CoP position, were applied since the CoP trajectory is usually invariant, while the joint angles had to be adjusted when the environmental condition changed. Using a simplified model of biped balance within a two-dimensional space, the stability of the robot behavior was discussed. This control law adaptively makes changes of the robot posture with respect to the slope angle, and the ankle joint torque becomes zero at this stationary posture; the moment produced by external forces is canceled by the moment of gravity. The zero ankle joint torque has an advantage from an energy consumption point of view.

Next, biped walking on both 5-degree upward and downward slopes was realized using a small biped robot we constructed. The experiments demonstrated the effectiveness of the control law based on feedback of the CoP and ground reaction forces. Neither the control law nor reference has to be adjusted even if a disturbance, which includes external forces caused by environmental changes, is unexpectedly exerted.

To guarantee the stability condition, the feedback gains Kd, Kp and Kf should be tuned in online to satisfy the Routh-Hurwitz criterion, because the parameters Cf and Cg depend on the θf that changes with respect to the external forces. Fortunately, in our experiments, the robustness of the control law covers this stability. We should discuss the area of the robustness more in our future works. In addition, we would like to achieve the biped, not only straight, on the slope.

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