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# A novel hierarchical control strategy for biped robot walking on uneven terrain

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***Abstract*— When position-controlled biped robot is blind walking on a uneven terrain at a high speed, huge foot contact impacts will be generated. However, traditional admitance control can't absorb the impact and stabilize the robot due to its slow response and Incompleteness. In this paper, we propose a control strategy including respectively designed swing leg control and support leg control with a new approach of control transition. For Swing leg control, double spring damping model is presented to optimize the admitance controller with faster response and better robustness, and a active foot height controller is also proposed to reduce the impact further. On the other hand, the control transition is accomplished by using a bionic fuzzy control. As a result, the foot contact impact can be reduced and the robot can blind walk fast on uneven terrain. Finally, the validity of the proposed strategy is confirmed by the simulation.**

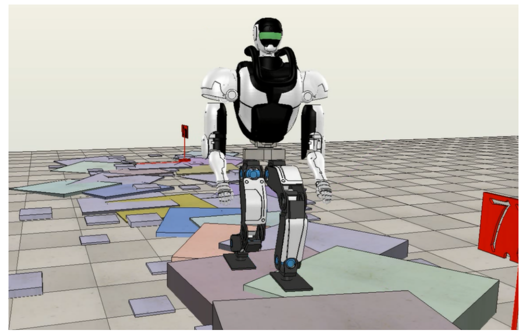

Fig. 1. Simulation of position-controlled biped robot BHR-6p blind walking on uneven terrain with preview control CoM trajectory planning and proposed control strategy. BHR-6p has a 1.6m height and a 45kg weight. The simulation walking speed is high up to 4km/h.

## I. INTRODUCTION

Position-controlled robots have many advantages. Their big gear ratio and good position following performance can simplify the control system, and many well elaborated algorithms [1-4] aiming at flat ground walking have been proposed. However, the high stiffness of position-controlled robots contradicts uneven terrain adaption.

Generally, visual perceived ground information is inaccurate and the time for trajectory adjustion is limited. Therefore, it is important to introduce a general control strategy to make robot self-adapted to uneven terrain with prespecified walking pattern.

Many research have been made to solve this problem. Kajita et al. [5][6] realized the stable walking on mild uneven terrain by applying posture/force following control which can track desired ZMP better. They transferred desired ZMP tracking to foot force/torque tracking and calculated position compensation for planing trajectories. However, unexpected impact generated by the swing foot stepping on a bump is critical, and that defferentiate swing leg control from support leg control. Therefore, the control of support leg and swing leg should be designed respectively.

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Luo et al. [7][8] divided support leg and swing leg control and apply different control methods on different swing leg procedures. However, this strategy is too strict with time that any unexpected disturbance during robot walking at a high speed may rebel the control sequence. Therefore, the control should be free from time and attached to walking status. Moreover, the fast walking speed lead to huge impact which can invalidate the well modeled controller. So the primary task is to reduce the impact, and then adapt to the uneven terrain.

When stepping on obstacles, robot's states can still deviate from its desired orbit. Based on capture point theory [9], some researches [10] accomplished horizontal step position adjustment to pull the states back to the original orbit. However, the swing foot may touch ground unexpectedly because of turbulence from uneven ground and compliance effect of support leg. Therefore, to reduce impact from these kind of touch, a vertical step adjustment should be developed. In this paper, we propose a Vertical Step Adjustment Controller based on impedance control and admitance control [11][12], which can reduce the foot contact impact further.

With the accumulation of previous researches [13], it is not difficult to design a controller to fit uneven terrain with impedance/admitance control [14] at low speed. But when robot walks faster, realizing the adaptation to uneven ground becomes a big issue. We concluded two main challenges:

- Absorbing the huge impact when swing foot contacts uneven ground.
- Designing a smooth and reliable control transition between swing leg and support leg.

In this paper, we realize stable and fast walking on uneven

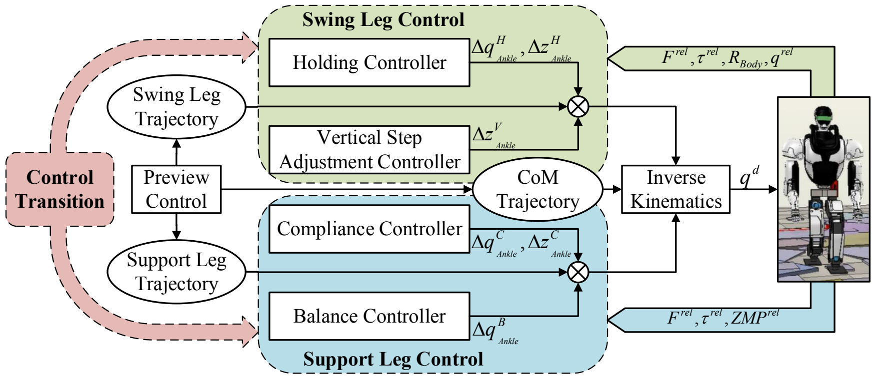


Fig. 2. Framework of hierarchical control strategy with Swing Leg control, Support Leg Control and Control Transition.

terrain by presenting a hierarchical control strategy solving two main problems above. The outer layer of the hierarchical control structure consists of three part: Support leg control, swing leg control and control transition realized by fuzzy control. For the inner layer of the structure: Swing leg control is parallel connected by Holding Controller and Vertical Step Adjustment Controller. Support leg control is parallel connected by Compliance Controller and Balance Controller.

The construction of this paper is as follows. We first present the framework of the control strategy in Section II. Then, we design the controllers of the control strategy Section III, followed by developing the control transition in Section IV. Following this we show the simulation results and verify the control strategy in Section V. Finally, we conclude the paper.

## II. CONTROL STRATEGY

The main purpose of proposed control strategy is to absorb feet landing impact and realize control transition. We need to consider clearly about the overall walking process and the formation of uneven ground. Luo et al's have already concluded the classification of obstacles and uneven ground, so we use the following indicators [7] to evaluate the performance of control:

- Height of stairs $h$.
- Pitch angle of slope $\alpha$.
- Roll angle of slope $\beta$.

Then we present the framework of proposed control strategy shown as Fig. 2 and all the adjustments are added to planned trajectory based on Preview Control.

### A. Swing leg

Swing leg absorbs impact when swing foot is landing and fit uneven ground. To absorb impact , we design a fast responding admitance controller to make the foot performs like a 3 DOF spring and absorbs impact passively. Then, vertical Step Adjustment Controller is designed to decrease the coming impact in advance actively and compute adjustment height $\Delta z^V_{Ankle}$. This controller requires for orientation of body $\boldsymbol{R}_{Body}$ and joints angle $q^{rel}$. Then we design another admitance controller to fit uneven ground by force&torque following.

To simplify the control system, we combine the passive impact absorbing admitance controller and the uneven ground fitting admitance controller by modeling a proper dynamic, which is to be presented later and we name it Holding-Controller. This controller computes adjustment angle and height $\Delta q^H_{Ankle}, \Delta z^H_{Ankle}$, while real force $F^{rel}$ and torque $\tau^{rel}$ of ankle are required. So Swing Leg Control is parallel connected by Holding Controller and Vertical Step Adjustment Controller.

### B. Support leg

Support leg needs to absorb impact when robot is shaking to make sure the support foot contact tightly to the ground. This is quite important to reduce uncertainty and make it easier to stabilize the robot. Admitance control is used to absorb impact like a 3 DOF spring and this controller is named Compliance Controller computing adjustment angle and height $\Delta q^C_{Ankle}, \Delta z^C_{Ankle}$ for ankle, and $F^{rel}, \tau^{rel}$ are required.

Noted that balance keeping is non-ignorable, we propose Balance Controller based on ZMP tracking to compute adjustment angle $\Delta q^B_{Ankle}$ for ankle and basically solved the paradox between balance and compliance by finding the adjustment rule of these two controller. This controller requires real ZMP of the support foot $ZMP^{rel}$. So Support Leg Control is parallel connected by Compliance Controller and Balance Controller.

### C. Control transition

Control transition requires the planned height of ankle and desired force of foot. When transit from swing leg to support leg, Holding Controller lock its adjustment and Compliance Controller start to work. This can make sure the robot adapt to the uneven ground and remain compliance at the same time.

## III. DESIGN AND MODELING OF CONTROLLERS

### A. Holding Controller and Compliance Controller

These two controller are the same in design and modeling process. They all make foot perform like a 3 DOF spring and realize force/torque following. The parameters of these two controller are specified respectively for different control purpose.

As shown in Fig. 3, we take double spring damping(DSD) as the model.

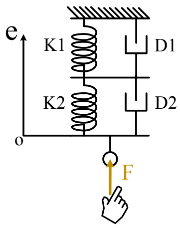


Fig. 3. DSD model for Holding Controller and Compliance Controller.

Define a state vector as $\boldsymbol{x} = [F \quad e \quad \dot{e}]^T$. The dynamics of DSD can be written as:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}u \tag{1}$$

where

$$\boldsymbol{A} = \begin{bmatrix} \frac{K_1+K_2}{D_1+D_2} & \frac{K_1K_2}{D_1+D_2} & \frac{K_1D_2+K_2D_1}{D_1+D_2} \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix},$$

$$\boldsymbol{B} = \begin{bmatrix} \frac{D_1D_2}{D_1+D_2} \\ 0 \\ 1 \end{bmatrix}$$

Parameters $K_1, D_1, K_2$ and $D_2$ are the elastic coefficients and damping factors of spring-damping system 1&2 respectively. $F$ represents force/torque inputs and $e$ represents position/angle outputs.

Parameters setting trick is shown as follows: $K_1$ is stiff(2000000 for vertical spring of holding controller in simulation), $D_1$ is small(1500), while $K_2$ is soft(20), $D_2$ is large(20000). Spring damping system 1 can absorb landing impact, which doesn't need to adjust a lot but requires a fast responce. While system 2 better for making swing foot fit the uneven ground, witch requires robustness. What's more, parameters of Compliance Controller is much larger than Holding Controller to provide a stiff support rather than to fit the ground.

Then desired force&torque can be computed by previous methods [5]. Then get the force/torque following controller by input the difference between real and desired force/torque:

$$\begin{cases} \ddot{e^d} = -k_1F^{rel} - k_2e^d - k_3\dot{e^d} & (2) \\ \ddot{e^p} = -k_1F^d - k_2e^p - k_3\dot{e^p} & (3) \end{cases}$$

where $\boldsymbol{e}^d$ represents desired trajectory for adjustment and $\boldsymbol{e}^p$ is original planed trajectory. Eq.(2) minus Eq.(3) we can get Holding Controller & Compliance Controller and realize force/torque following.

$$u = \Delta\ddot{e} = -k_1(F^{rel} - F^d) - k_2\Delta e - k_3\Delta\dot{e} \tag{4}$$

where feedback gains can be calculated by LQR optimal control.

In addition, Compliance Controller can also be applied on hip joints to provide a better compliance.

## B. Vertical Step Adjustment Controller

There are 3 main cases that lead to unexpected ground touch of swing foot:

- Compliance effect of support leg.
- Support foot doesn't fit well with ground.
- Step on stairs.

this controller can theoretically solve the problem in first two case, and ease impact in the third case.

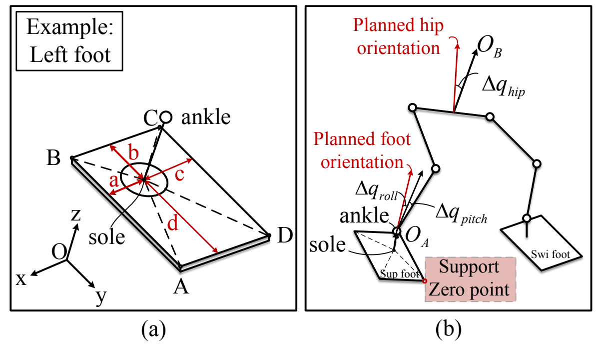


Fig. 4. (a) shows parameters of foot and the method to find out the Nadir. (b) shows important parameters of robot whole body and presents a method to compute the height of the Nadir.

First of all we calculate the height of the Lowest-Point(Nadir) of swing foot. Robot body orientation $\boldsymbol{O}_B$, support foot orientation $\boldsymbol{O}_{A.sup}$ are define as follows:

$$\boldsymbol{O}_B = \begin{bmatrix} Pitch_B \\ Roll_B \end{bmatrix} \tag{5}$$

$$\boldsymbol{O}_{A.sup} = \begin{bmatrix} Pitch_{A.sup} \\ Roll_{A.sup} \end{bmatrix} \tag{6}$$

Planned angle for ankle roll is smaller than 10°, so the coupling of ankle pitch & roll can be simplified as vector addition. Furthermore, $\boldsymbol{O}_{A.sup}$ and $\boldsymbol{O}_B$ are all vertical, so we can get $\boldsymbol{O}_{A.sup}$:

$$\boldsymbol{O}_{A.sup} = \boldsymbol{O}_B \quad \begin{bmatrix} \Delta q_{pitch} + \Delta q_{hip} \\ \Delta q_{roll} \end{bmatrix} \tag{7}$$

As shown in Fig. 4(b), $\Delta q_{pitch}$, $\Delta q_{roll}$ are adjustment angle of ankle pitch & roll respectively and $\Delta q_{hip}$ is adjustment angle of hip. $\boldsymbol{O}_B$ can be measured from IMU.

With $\boldsymbol{O}_{A.sup}$ and joints angle from encoders, Nadir of each foot can be judged. Take left swing foot for example in Fig. 4(a):

$$\begin{cases} {}^B\boldsymbol{P}_{sup} = {}^B\boldsymbol{T}_{A.sup}{}^A\boldsymbol{P}_{sole.sup} & (8) \\ {}^B\boldsymbol{P}_{swi} = {}^B\boldsymbol{T}_{A.swi}{}^A\boldsymbol{P}_{sole.swi} & (9) \end{cases}$$

$$h = \boldsymbol{R}_{foot.sup}(h_{ankle} + {}^{ankle.sup}\boldsymbol{T}_{hip.swi}{}^B\boldsymbol{P}_{swi}) \tag{10}$$

Eq.(8)&(9) do the coordinate transformation of sole from ankle frame to body frame. Then we get the height of left foot's sole $h$ with Eq.(10). $\boldsymbol{R}_{foot.sup}$ can be get from $\boldsymbol{O}_{A.sup}, h_{ankle}$ is the height of ankle and ${}^{ankle.sup}\boldsymbol{T}_{hip.swi}$ is the transfer matrix.

$$\begin{bmatrix} h_A & h_B & h_C & h_D \end{bmatrix} = h + \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \boldsymbol{R}_{foot.swi}\boldsymbol{\Gamma} \tag{11}$$

where machine dimension of foot is defined as:

$$\boldsymbol{\Gamma} = \begin{bmatrix} a & a & -c & -c \\ d & -b & -b & d \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Then calculate the heights of four points shown in Fig. 4(b) with Eq.(11) and find the lowest one as the Nadir. Take the Zeropoint as height of 0, the height of the Nadir is represented as $h_{min}$.

$$\Delta Z_{ankle} = \frac{kp_1 + kd_1 s}{kp_2 + kd_2 s + m_2 s^2}(h_{min} - Z^p_{ankle}) \quad (12)$$

Through the Impedance-Admittance system, smooth height adjustment of swing leg ankle can be obtained by Eq.(12). $Z^p_{ankle}$ is the planned ankle height trajectory.

### C. Balance Controller

This controller has two main mission:

- Resolve the paradox with Compliance Controller.
- Keep balance by ZMP tracking.

Consider the paradox first. Compliance and balance often have the opposite effect. When robot step on a variable slope, Compliance Controller should play a leading role first to absorb the impact, then Balance Controller take it over to keep balance. That means the adjustments of Balance Controller should be slower and larger.

We build a static model for robot shown as Fig. 5:

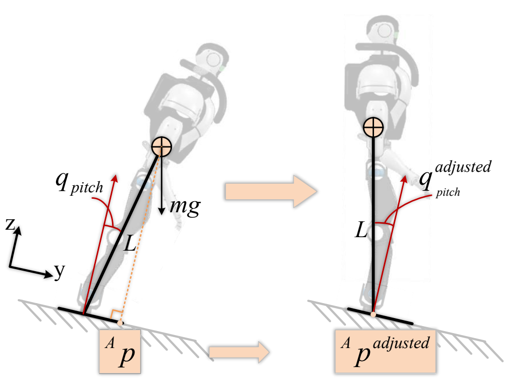


Fig. 5. Static invert pendulum model for Balance Controller. When robot's body is not upright, ZMP moving away from the ankle. Then control the pitch angle to pull ZMP back to the ankle and keep robot upright.

Dynamics of the model can be described as Eq.(13):

$$\begin{cases} mg\sin(q_{pitch})L = mL^2\ddot{q}_{pitch} \\ {}^AP = L\sin(q_{pitch}) \end{cases} \quad (13)$$

where $^Ap$ represents ZMP on the slope in ankle frame and it's same the projection of CoM to the slope. Replace $\sin(q_{pitch})$ and take the Laplace transform, we get Eq.(14):

$$^AP_{calculated} = \frac{L^2}{g}s^2 q_{pitch} \quad (14)$$

then we add a one order inertia object to imitate the lag of system. Eq.(15) shows the relationship between real ZMP: $^AP_{real}$ and calculated ZMP: $^AP_{calculated}$.

$$^AP_{real} = \frac{1}{1+Ts}{}^AP_{calculated} \quad (15)$$

Define a state vector as $\boldsymbol{\chi} = [{}^AP_{real} \quad q_{pitch} \quad \dot{q}_{pitch}]^T$. The system equation is obtained by combining Eq.(14)&(15):

$$\dot{\boldsymbol{\chi}} = \boldsymbol{\Lambda}\boldsymbol{\chi} + \boldsymbol{E}u \quad (16)$$

where

$$\boldsymbol{\Lambda} = \begin{bmatrix} \frac{1}{T} & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix},$$

$$\boldsymbol{E} = \begin{bmatrix} \frac{L^2}{gT} \\ 0 \\ 1 \end{bmatrix}$$

Balance-Controller is given by Eq.(17) to control $^AP_{real}$ tardily toward 0 and realize adjusting the robot upright.

$$u = \Delta\ddot{q}_{pitch} = -k_1{}^AP_{real} - k_2\Delta q_{pitch} - k_3\Delta\dot{q}_{pitch} \quad (17)$$

## IV. CONTROL TRANSITION

### A. What do humans do when switching legs

Some patterns are shown when humans is walking. When swing foot is away from the ground and not stressed, calf muscles is in relax. While the foot become closer to the ground and is applied on force, the calf muscles tighten gradually and become support foot. We abstract features from this pattern as shown in Fig. 6:

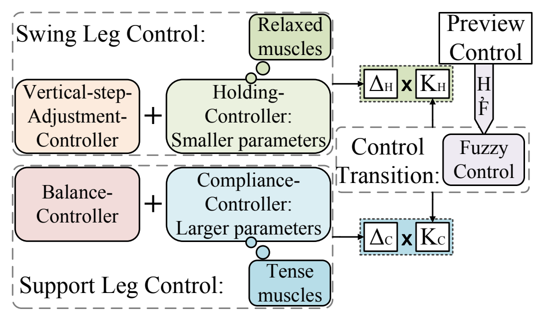


Fig. 6. Control Transition and effect of control coefficients $K_H$&$K_C$.

$H$ and $F$ are the planned height of ankle and desired force respectively generated by Preview Control. Then Control Transition generate control coefficients $K_H$ and $K_C$ for swing leg control and support leg control severally. Since these two paralleled control operate simultaneously, control weight is distributed by the control coefficient, and it's proposed that $K_H + K_C \equiv 1$. We can realize the transition by generating $K_H$.

Now we know that if $H$ is high and $F$ is small, $K_H$ should be big, That means swing leg control is dominant to imitate a relaxed foot fitting uneven ground. If in the contrary situation, support leg control plays the main role. However, there is no specific linear relationship between $H$, $F$ and $K_H$, so we use fuzzy control to correlate them.

### B. Fuzzy knowledge base

We fuzzify $H$, $F$ and $K_H$ as Fig. 7 Shows. (a)&(b) are the inputs and (c) is the output. The fuzzyfication depends on planning method and robot platform.

TABLE I shows the knowledge base which is based on our experience. We testify it with simulation and the result

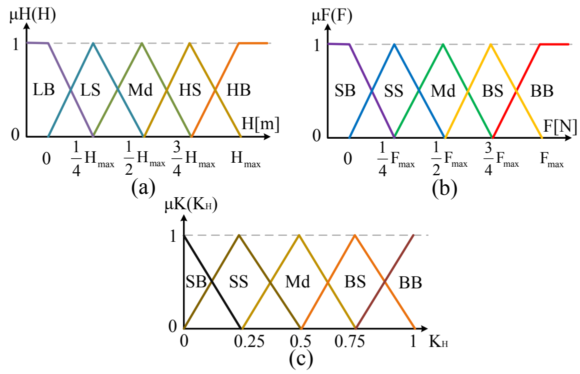


Fig. 7. Membership function of $H$, $F$ and $K_H$.

TABLE I
KNOWLEDGE BASE OF CONTROL TRANSITION FUZZY CONTROL

| $K_H$ | | $H$ | | | | |
|---|---|---|---|---|---|---|
| | | LB | LS | Md | HS | HB |
| $F$ | SB | Md | BS | BS | BB | BB |
| | SS | Md | Md | BS | BB | BB |
| | Md | SS | Md | BS | BS | BB |
| | BS | SB | SS | Md | BS | BB |
| | BB | SB | SS | Md | BS | BB |

is shown as Fig 8. And Control Transition process can be expressed as Eq.(18).

$$(K_H, K_C) = fuzzy(H, F) \tag{18}$$

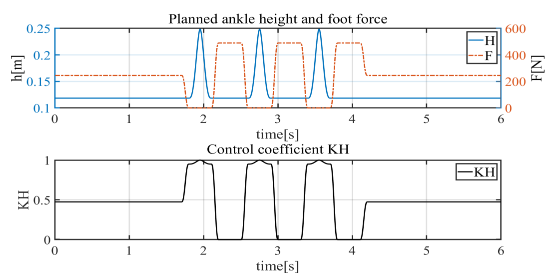


Fig. 8. Input $H$, $F$ and output $K_H$

## V. SIMULATION

### A. Impact absorbing

We set DSD parameters as presented in section II and compare it with simple spring damping model by giving them a step force input. The result is shown as Fig. 9. DSD model responds faster at the beginning to absorb impact, then adjust slower when fitting uneven ground to provide better stability which is important to avoiding feet coupled vibration.

Fig. 10 Shows the performance on impact absorbing of proposed swing leg control. The robot's left foot step on a stair at the 2nd step. Controlled leg can reduce the maximum contact force by 53.6%. However, the robot only be controlled with a spring damping controller falls after the impact. This simulation validate proposed Swing Leg Control and the model of DSD.

### B. Balance keeping

Snapshots of the simulation are shown as Fig. 11, and Fig. 12 Shows the result. The robot crouch down at first,

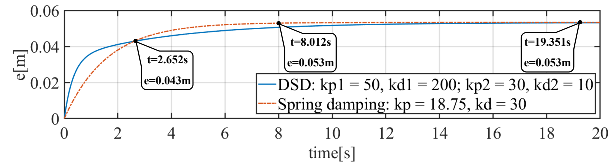


Fig. 9. Step responce of DSD & spring damping

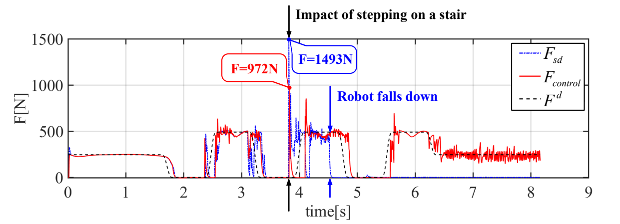


Fig. 10. Simulation result of impact absorbing with proposed Swing Leg Control comparing with only controlled by a spring damping controller

then the slope rotates clockwise, and then the slope rotate counterclockwise. Fig. 12 Shows that Balance Controller is opposite to Compliance Controller, the later responds faster but weaker than the former. The combination of these two controller make the robot stable and balanced on the rotating slope. The tolerant slope angle is -12.5°to 8.3°.

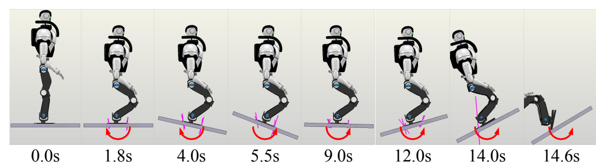


Fig. 11. Snapshots showing the BHR-6p robot keeping balance on a rotating slope. The rotational speed is 5.73°/s.

Finally the robot fall because the Angle is too big and the rotating speed is fast. This simulation validate the idea to solve the paradox between compliance and balance.

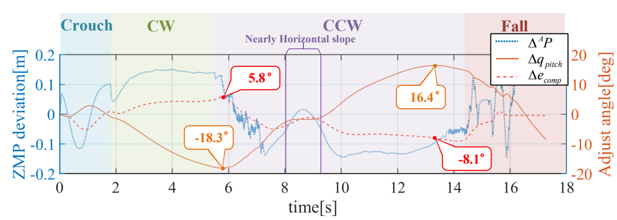


Fig. 12. ZMP deviation $\Delta^A P$, Balance angle $\Delta q_{pitch}$ and compliance angle $\Delta e_{comp}$ of the left leg during the BHR-6p standing on a rotating slope.

### C. Walking fast on uneven terrain

We test BHR-6p to walk on a complex uneven terrain, the snapshots of the simulation is shown as Fig. 13. In the simulation BHR-6p complete the specified indicators in TABLE II. More complicate situations happened in the simulation and proposed control strategy success to make BHR-6p walk through all the obstacles.

The result of the simulation is plotted in Fig. 14. We observe (a) that real force is following the desired one with fluctuation and strike. That may be caused by the lag of the controller and the errors of force sensors. Then in (b), support

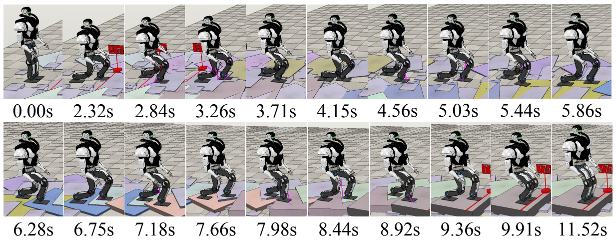


Fig. 13. Snapshots of BHR-6p walking fast on uneven terrain controlled by proposed strategy.

TABLE II

SPECIFIED INDICATORS FOR SIMULATION

| | |
|---|---|
| $Walking\ speed$ | 4.09km/h |
| $h$ | 4cm |
| $\alpha$ | 5° |
| $\beta$ | 2° |

signal goes high is representing left foot support, at middle is representing right foot support, 0 means double support. Adjustment height changes quickly during each foot's swing phase to fit the fluctuant ground and goes back to the origin every period to provide a stable control. In (c) we can observe the ZMP tracking is Not particularly good. Nevertheless, our control strategy is designed to provide the desired foot force for walking. Errors from force sensors and the model of trajectory planning rebel the desired force which lead to a poor ZMP tracking. Real ZMP has the same pattern with planning one and that is adequate to validate the control strategy.

## VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed a novel control strategy for biped robot to walk stable and fast on uneven terrain. The control strategy includes three part: Support leg control, swing leg control and control transition. The swing leg control have better impact absorbing capacity, and the validity of the proposed strategy has been verified by simulations. The contributions of this paper are summarized as follows:

- Proposed a novel control strategy for biped robot to walk fast on uneven terrain.
- Designed an appropriate virtual model for admitance control.
- Presented a vertical step adjustment controller.
- Developed a balance controller based on ZMP tracking.
- Accomplished control transition for support leg control and swing leg control based on a bionic idea.

This control strategy is now testing on real platform: BHR-6p. In the future, we can apply buffer gears to absorb higher frequency percussion. Moreover, the trajectory planning can be optimized to reduce joints speed. Furthermore, we can develop a reliable state estimation to realize on-line control transition.

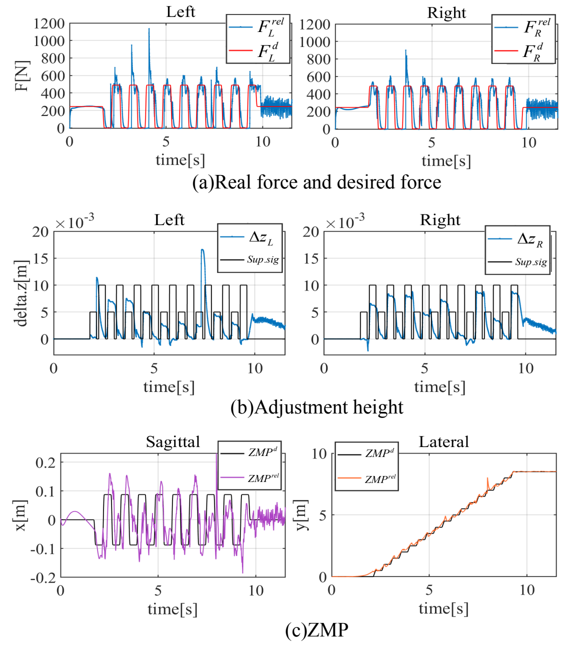


Fig. 14. Simulation result.

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