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Backstepping-based control for a new semi-passive biped model

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Abstract. In this work, we propose a new Semi-Passive Biped (SPB) Model and a Center of Gravity Shift (CGS) control method of this model. The passing friction between the swing leg and the ground of passive robots' locomotion consumes robots' energy, resulting in the model can't walk passively. In order to analyze this problem in a more practical way, we propose a new SPB Model and analyze its energy consumption. Also, we suggest a CGS control method, which can make the proposed new SPB model walk stable. Finally, an illustrative experiment is presented to verify the SPB model and the effectiveness of the CGS control method.

Keywords: center of gravity shift, semi-passive biped, passing friction, compass gait model, backstepping

1. Introduction

Biped robot technology is one of the most important technologies to promote the development of future science and technology. It has received widespread attention in recent years. The ASIMO robot released by Honda of Japan [1], the REEM C biped robot developed by PAL Robotics of Spain [2], and the latest version of the Atlas biped robot released by Boston Dynamics of the United States in 2016 [3]. These three types of robots demonstrate excellent walking ability. However, when these robots are walking, the joints of the whole body of the robot need to be controlled in real-time. During the walking, the energy consumption is huge, the energy efficiency is relatively low, and the walking is not flexible. In order to improve these problems faced by biped robots in walking, we need to start from the dynamic characteristics of passive gait biped robots with extremely high energy utilization, and study the reasons for the extremely high energy efficiency in passive gait. The initial purpose of researching passive dynamic models is to explore how humans can walk in an energy-efficient way which can be used to design human-like robots.

During the single-leg support period in the process of robot walking, all the weight of the robot is pressed on the stance leg, and the component force of the total gravity in the direction perpendicular to the slope surface is the supporting force of the slope surface to the stance leg. Human beings will use a slight shift of the center of gravity to prevent the swinging leg from rubbing against the ground during the swinging process [4-5]. When walking on relatively soft ground, the pressure of the body on the ground will cause the soft ground to deform, causing friction between the swinging leg and the ground during the swinging process to become greater. In such a situation, humans beings usually increase the amount of center of gravity shift (CGS) to leave more room for the swinging leg to swing forward [6].

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Main contributions:

1. In this paper, we propose a new semi-passive biped (SPB) model with the passing friction, which is the friction between the swing leg and the sloped surface in the period of swing. And we also analyze that raising the angle of the slope can be increase the gravitational potential energy of the model, so that offset the consumption of friction in the model.

2. In order to achieve energy-efficient control of robots in more realistic circumstances, we propose a CGS control to avoid the swing leg rub with the slope basing on different softness coefficients of different ground materials.

The remaining chapters are arranged as follows: Chapter 2 discusses related work; Chapter 3 describes the problem we considered; Chapter 4 provides a basic description of the model and obtains the kinematics equations of the system through mechanical analysis and mathematical calculations; Chapter 5 designs a backstepping controller to control the model. Chapter 6 sets some simulation experiments of the proposed model and verify the effectiveness of the controller; Chapters 7 to 9 are the results, discussion and conclusion parts.

2. Related work

The passive dynamics theory of biped walking was first proposed by Canadian scholar Tad McGeer[7]. He established a biped robot passive walking model, and designed a simple kneeless passive walking robot. In the passive walking model, the robot does not rely on any active control, and can walk stably on the inclined ground only by gravity. In addition to the passive walking robot with a simple structure, Tad McGeer also studied passive robots with more complex structures [8]. Goswami et al. [9], Marianoet al. [10] established the walking model and analyzed its stability.

In order to make the unpowered biped walking robot to achieve more stable, more complex, and more adaptable walking, the robot needs to be controlled. Bifurcations and chaos are key components to the analysis and control of unpowered biped walking robots [11-14,24]. Poincaré map is an efficient and valid method to analyze the passive dynamic walking of the compass-gait biped robot and expressed and recently simplified in [15-16,25]. OGY-based feedback control is another control method be investigated by many researchers in [13,22,27-29]. [30] illustrated that limit cycles are an effective method to determine the stability of the model. These control methods achieve effective control of the passive dynamic model, allowing the model to perform better, but controlling of the whole process will increase energy consumption, which is somewhat deviated from our purpose of studying the passive model.

Many researchers have done a lot of work on how to make the robot model closer to reality. Recently, many researchers have done research on the establishment of robot dynamics models. [17,18] considered the problems that happened in the real locomotion of robots. [19] added torso in the model which is similar to a real human. [20] designed semicircular feet for the model to gain more stability. The problem of heel Strike is considered in [21]. In order to simulate human walking, [23,31] designed a new model with a sole foot and analyzed its stability. [26] used the elastic energy to improve the walking ability of the model by adding spring between the hip and the leg. [32] considered a model of a robot with knees in the middle of legs, which is more realistic. However, the passing friction of the swing leg should be considered in the swing process which occurs between the swinging leg and the slope surface when it swung to overlap with the standing leg. The energy consumed by this friction existed in every step of walking no matter which model is considered. Many researchers have paid attention to this point, [33] changed the hard slope to elastic, the pressure of the robot on the slope will deform the slope. However, since the slope is considered as a whole plane, the slope surface moves as a whole at the moment when the robot's two-leg support and single-leg support are switched. But we know that the softer the ground, the less it will affect the entire plane when it is under pressure at a certain point. The deformation only occurs at this point.

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3. Problem statement

The main problem we consider is the passing friction of the swinging leg of the robot when walking on soft ground. According to the work of Garcia et al. [10], We divide the entire process into single steps, as shown in Figure.1. Figure. 1(b) describes the variables and parameters we use and Figure. 1(d) is the moment with passing friction.

Since [4] modeled a flexible passive walker which regarded the whole slope as a plane with the Hunt-Crossley contact model, there might be a problem. Generally speaking, the soft ground which is elastic and viscous is deformed only around the pressure point, and other positions will not be affected. It is unreasonable for the slope surface to be regarded as a whole because this model will cause the situation that when one point is pressed down, other places will also tilt. In this article, we integrate the elasticity of the soft ground into the leg structure of the robot, which can express the characteristics of the elastic ground and also make the model very simple.

In this research, we assume that the collision and bipedal conversion process is completed in an instant, and the foot will not bounce when colliding with the slope. Moreover, the friction coefficient of the slope is large enough to ensure that the stance foot does not slide relative to the ground.

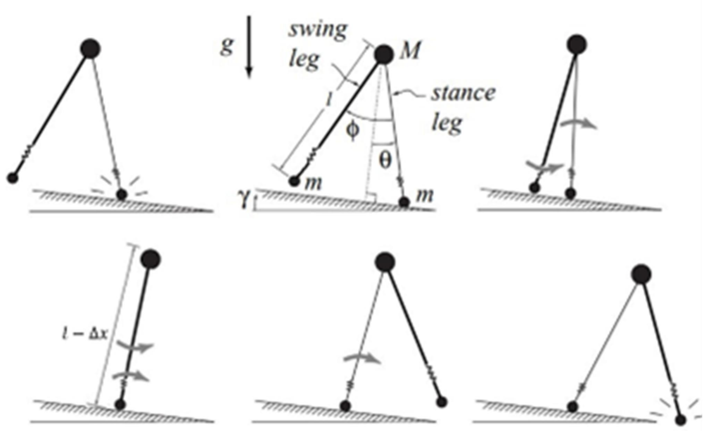


Figure 1. One step of the Compass Gait Model(θ is the angle of the stance leg with respect to the slope normal, and ϕ is the angle between the stance leg and the swing leg. γ is the angle of the slope).

4. Methods

In the model, we put the softness of the ground into the design of the robot's legs, and the adjustment of the parameters can indicate that the robot is walking on the ground with different degrees of softness. According to the spring force formula

$$F_N = k\Delta x \tag{1}$$

where F_N is the pressure received in the direction of spring deformation, which is equal to the normal contact force of the slope surface to the robot's stance leg, that is, the component force of the robot's gravity in the direction perpendicular to the slope surface. k is the softness coefficient of elasticity of the spring, which indicates the softness of the ground and varies according to the material of the ground. Δx is the amount of deformation of a spring under pressure, here it refers to the depth of the sinking of the stance leg.

So we can get how much the robot's stance leg sinks on the soft ground, that is Δx. Since the distance from the surface of the slope to the hip of the robot is less than the length of the swing leg, the swinging leg will rub against the ground during the swinging process, where the friction is described as Equ. (2)

$$f = \mu F_N \tag{2}$$

where μ is the coefficient of friction of the ground and f is the tangential friction force experienced by the swing leg.

The friction force is obtained by calculating the resultant force with gravity along the direction of the slope surface as

$$f = \mu\cos\gamma - \sin\gamma \tag{3}$$

The friction time of the swinging leg should be determined by the softness coefficient of the ground. Through mathematical calculations, when the angle between the legs meets $\cos\frac{\phi}{2} > \frac{l-\Delta x}{l}$, the swinging leg will be rubbed by the ground.

Because the swing leg of the robot only receives friction when it passes the slope during the swing process, we divide the swing locomotion into three phases: 1. The swing leg is above the stance leg; 2. The swing leg is passing the slope; 3. The swing leg is below the stance leg. Both in the first and third periods of swing, the swing leg is only affected by gravity, so that the swing leg can be considered as a simple pendulum model.

This nonlinear system can be described by Eq.(4).

$$\begin{bmatrix} 1+2\beta(1-cos\phi) & -\beta(1-cos\phi) \\ \beta(1-cos\phi) & -\beta \end{bmatrix} \begin{bmatrix} \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} + \begin{bmatrix} -\beta sin\phi(\dot{\phi}^2 - 2\dot{\theta}\dot{\phi}) \\ \beta\dot{\theta}^2 sin\phi \end{bmatrix} + \begin{bmatrix} (\beta\frac{g}{l})[sin(\theta-\phi-\gamma) - sin(\theta-\gamma)] - \frac{g}{l}sin(\theta-\gamma) \\ (\beta\frac{g}{l})[sin(\theta-\phi-\gamma)] \end{bmatrix} = Bu \tag{4}$$

where $\beta = \frac{m}{M}$ is the ratio of the mass of the foot to the mass of the body and θ, ϕ are functions of time t defined above. Eq.(4) represents angular momentum balance about the foot for the SPB model and about the hip for the swing leg, respectively. Because of the assumption of mass, setting $\beta = 0$ in the first equation of motion and dividing through by β in the second and rescaling time by $\sqrt{l/g}$ in simplification. B is the coefficient of the controller and u is the controller and $u = 0$ while there is no extra force on the robot. Then we get Eqs. (5) and (6) as follow. We use Eqs. (5) and (6) to describe the locomotion of the robot in the first and third periods of the swing phase.

$$\ddot{\theta}(t) - sin(\theta(t) - \gamma) = 0 \tag{5}$$

$$\ddot{\theta}(t) - \ddot{\phi}(t) + \dot{\theta}(t)^2 sin\phi(t) - cos(\theta(t) - \gamma)sin\phi(t) = 0 \tag{6}$$

In the second period of the swing phase, we regard the swing leg as a simple pendulum model with friction. Based on Newtonian mechanics, we calculate the kinematic equation of the swing leg. The kinematics equation of a simple pendulum model with friction can be obtained as follows:

$$F_n + M = I\rho \tag{7}$$

where F_n and M are the moments of friction and other forces respectively. $I = ml^2$ is the moment of inertia of the pendulum, and $\rho = \frac{d^2\phi}{dt^2}$ is the angular acceleration of the pendulum.

Then we establish the equations of the second phase with the friction moment in it. After simplification, the equations of the second phase are Eqs. (8) and (9).

$$\ddot{\theta}(t) - sin(\theta(t) - \gamma) = 0 \tag{8}$$

$$\ddot{\theta}(t) - \ddot{\phi}(t) + \dot{\theta}(t)^2 sin\phi(t) - cos(\theta(t) - \gamma)sin\phi(t) + sin(\gamma) - \mu cos(\gamma) = 0 \tag{9}$$

where μ is the friction coefficient of the slope.

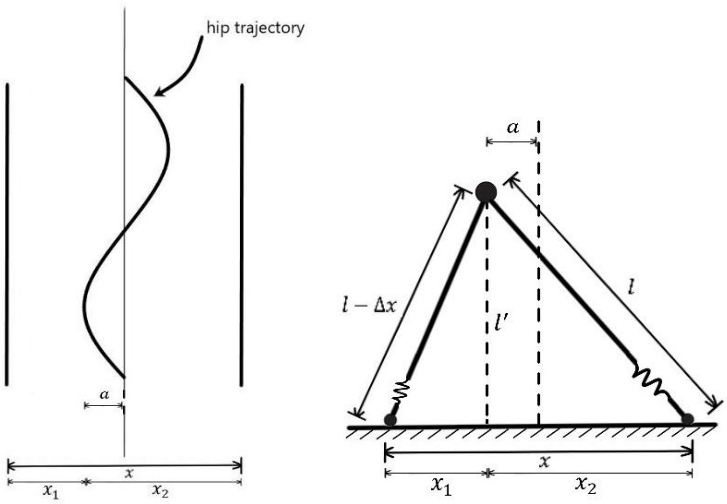
5. Controller design

In order to solve the problem of passing friction with the most energy-efficient method, we propose a CGS control, so that the robot controls the body's center of gravity offset so that the swinging leg does not touch the ground.

During the movement of the robot, the trajectory of its hips should be a combination of two sinusoids. One in the vertical direction, which is the trajectory generated by the simple pendulum movement of the standing leg of the robot during the forwarding process. The other is in the horizontal direction. And this is used to solve the problem We supposed. When the swinging leg swings to a vertical position, the robot's hips are far away from the centerline of the robot's body. And when the moment that two legs are supported, the robot's hips It's on the midline of its body.

We only control the horizontal trajectory of the hip and no external force is applied to the movement in the vertical direction.

In order to avoid passing friction by controlling the horizontal swing of the robot's hips, we first plan the desired trajectory of model’s hip according to the depth of the stance leg sinking in the ground. From a top view, the robot's hip movement is move in a trajectory as Figure. 2(a). The softer the ground, the deeper the stance leg sinks, and the greater the amplitude of the hip trajectory is required to prevent the swinging leg from touching the ground.



(a) The top view (b) The front view

Figure 2. The top view and front view of robot locomotion.

The amplitude is calculated through the front view as Figure. 2(b). Construct geometric relationships as Equ. (10).

$$\begin{cases} l^2 = {x_2}^2 + l'^2 \\ (l - \Delta x)^2 = {x_1}^2 + l'^2 \end{cases}$$

(10)

After simplification, we can get the amplitude a of the desired trajectory of the hip.

$$a = \frac{x_2 - x_1}{2} = \frac{1}{2x}\left(l^2 - (l - \Delta x)^2\right) \tag{11}$$

So the trajectory of the hip in the horizontal direction is described as Equ. (12)

$$y_r = a \sin x$$

(12)

We only design the controller with the hip in the horizontal direction, the state $q = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}$, q_1 and q_2 are the position and speed of the hips respectively, the equation of state is

$$\begin{cases} \dot{q}_1 = q_2 \\ \dot{q}_2 = \bar{u} \end{cases}$$

(13)

$$y = q_1$$

(14)

where $\bar{u}$ is the controller of model.

Step 1: State coordination first

$$e_1 = y_r - y \tag{15}$$

$$e_2 = x_2 - \alpha_1 \tag{16}$$

Design Lyapunov Function as

$$V_1 = \frac{1}{2}{e_1}^2 \tag{17}$$

Take the derivative of the Equ. (17) and we can get

$$\begin{aligned} \dot{V}_1 &= e_1\dot{e}_1 \\ &= e_1(\dot{y}_r - \dot{x}_1) \\ &= e_1(\dot{y}_r - e_2 - \alpha_1) \end{aligned} \tag{18}$$

The virtual controller is designed as

$$\alpha_1 = e_1 + \dot{y}_r \tag{19}$$

Taking Equ. (19) into Equ. (18) and gain

$$\begin{aligned} \dot{V}_1 &= -{e_1}^2 - e_1e_2 \\ &\leq -\frac{1}{2}{e_1}^2 + \frac{1}{2}{e_2}^2 \end{aligned} \tag{20}$$

Step 2: Design Lyapunov Function as

$$V_2 = \frac{1}{2}{e_2}^2 \tag{21}$$

Take the derivative of the Equ. (21) and we can get

$$\begin{aligned} \dot{V}_2 &= e_2\dot{e}_2 = e_2(\dot{x}_2 - \dot{\alpha}_1) \\ &= e_2(\bar{u} - \dot{e}_1 - \ddot{y}_r) \end{aligned} \tag{22}$$

The controller can be designed as

$$\bar{u} = -e_2 + \dot{e}_1 + \ddot{y}_r \tag{23}$$

Taking Equ. (23) into Equ. (22) and gain

$$\dot{V}_2 = -{e_2}^2 \tag{24}$$

For the whole system, the Lyapunov Function is

$$V = V_1 + V_2 \tag{25}$$

The derivative is

$$\begin{aligned} \dot{V} &= \dot{V}_1 + \dot{V}_2 \\ &= -\frac{1}{2}{e_1}^2 - \frac{1}{2}{e_2}^2 \end{aligned} \tag{26}$$

Under the CGS control, the robot's hip can track the desired trajectory, and this trajectory can ensure that the robot does not receive friction from the ground during its movement. Compared to applying full control to the robot, we take advantage of the passive robot's own characteristics of passive movement. Only a CGS controller designed in the horizontal direction can allow the robot to continue to maintain passive movement characteristics on different soft ground. This is the advantage of what we called a semi-passive model.

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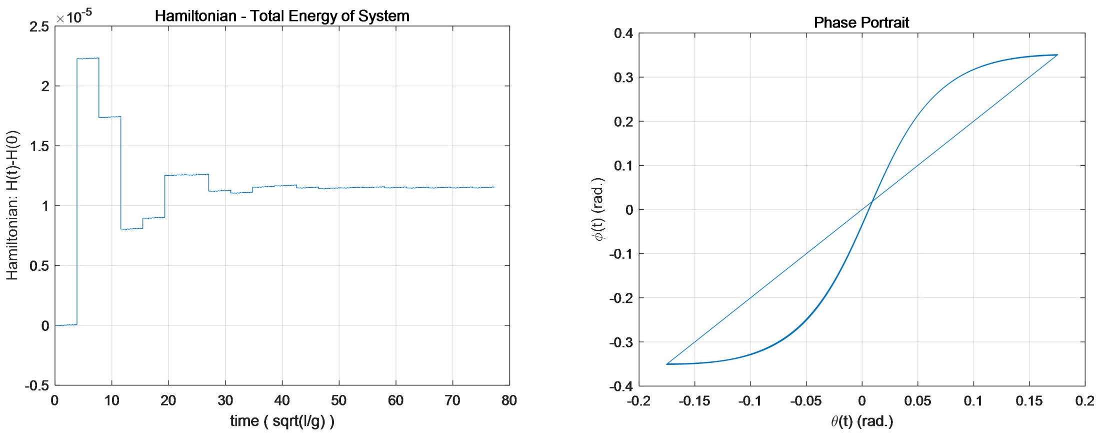
6. Experiments

According to the work of Andrew D., we establish the simulation of the SPB model in MATLAB 2020a. Our simulation experiment is divided into the following steps and demonstrates that the energy consumption of passing friction influence the stability of the passive walking model.

We set 20 steps of locomotion. The slope angle is $\gamma = 0.006$. The length of leg is $l = 1.5m$. Acceleration of gravity $g = 9.8\,N/m^2$. The model mass $M = 5kg$, $M = 0.05kg$.

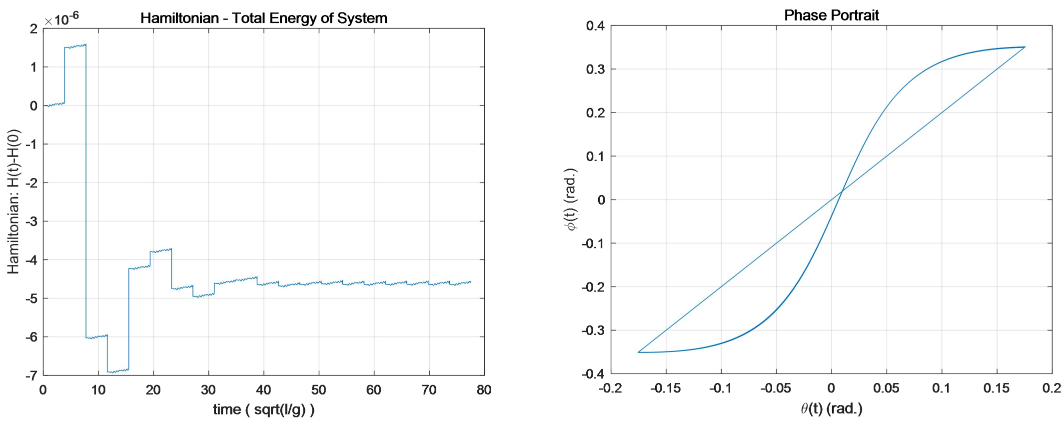
First, in the ideal Compass Gait Model, the elastic coefficient $k = 0$. After analyzing the simulation results, we determined the criteria for judging the locomotion of the model. We use the Hamiltonian to judge whether the energy of the model is enough to move forward passively, and use the phase portrait to judge whether each step locomotion of the model is stable. The Hamiltonian and phase portrait when $\gamma = 0.006$ is shown in Figure. 3.



(a)Hamiltonian (Energy) (b) Phase Portrait

Figure 3. Ideal Model without Friction.

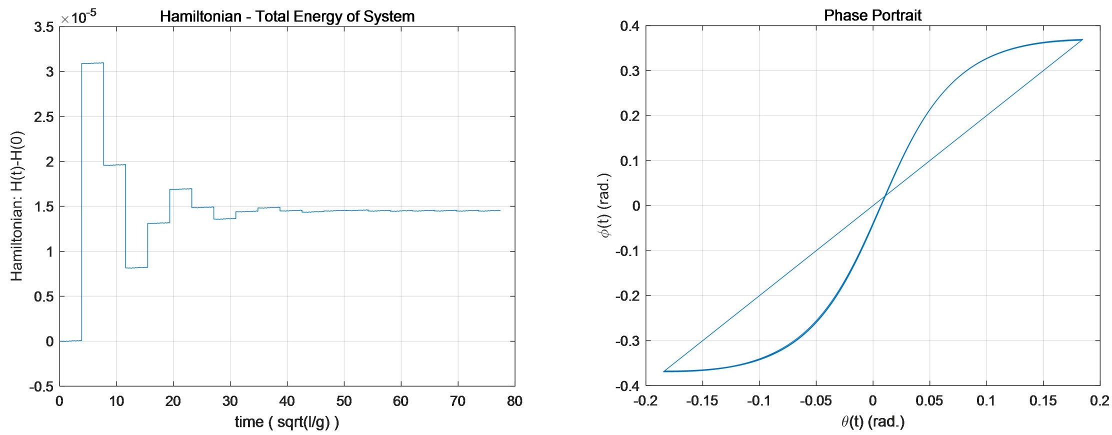
Second, set the elastic coefficient of ground $k = -1666\,N/m$ and the friction coefficient $\mu = 0.007$. Let the swing leg experience a period of passing friction as the foot passes the surface of the slope. After calculation, while the angle between two legs $cos\,\phi > 0.98$, the swing leg will rub the ground. The Hamiltonian and phase portrait is shown in Figure. 4.



(a)Hamiltonian (Energy) (b) Phase Portrait

Figure. 4. Model with Friction.

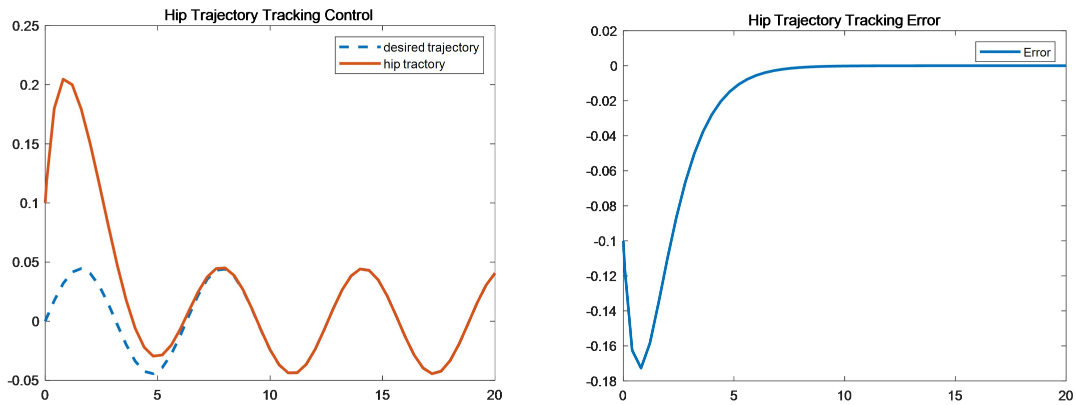
On the basis of the second step, we change the angle of the slope to provide the robot with greater gravitational potential energy into its kinetic energy. Figure. 5 represents that when increasing the slope angle (γ) to 0.007, the SPB model has positive energy and the phase portrait is stable for each step. So the robot can step forward steadily in reality.



(a)Hamiltonian (Energy) (b) Phase Portrait

Figure. 5. Increase Slope Angle of Model with Friction.

Finally, the experiment of CGS control. After calculation, the amplitude of the expected trajectory $y_r = 0.04455 \sin t$. The controller is designed as $u = -e_2 - 0.04455 \sin t + 0.04455 \cos t - q_2$. The hip trajectory and error are shown in Figure. 6(a) and (b).



(a) Hip trajectory (b) Trajectory Error

Figure. 6. Hip trajectory control.

7. Results

In this paper, we proposed a new SPB model that walks on the ground with varying hardness, which takes into account the inevitable friction between the swing leg of robots and the ground. This is an important finding in the appliance of biped robots. According to Figure. 4, after a few steps forward, the energy of the system becomes negative, so even if the phase portrait shows the locomotion is stable, the robot cannot continue to step forward actually. Figure. 5shows that the angle of the slope affects the energy of the robotic system. After designing a CGS controller, the model can walk in the desired hip trajectory according to the different softness of the ground, and the swing leg will not rub with ground.

8. Discussion

The results indicate that the robot can walk passively with the hip controller which can avoid the swing leg's friction with the ground when the external environment cannot be changed in actual applications. The new model suggests a simpler method to solve the realistic problem. These results should be taken into account when considering how can a biped robot stably walk on different ground. The generalizability of the results is limited by the knowledge of the elastic coefficient of ground.

Under the CGS control, the hip trajectory could be used to avoid the passing friction which will consume the energy of the robot. Also, we demonstrate the effectiveness of this proposed control method with simulation experiments. Further research is needed to establish adaptive control methods and let the robot adjust the parameters by itself.

9. Conclusion

This paper proposes a new SPB model that can walk on slopes with different degrees of softness, and solve the problem of passing friction through CGS control. Passing friction is a factor that must be considered in robot locomotion. Passing friction will make the passively moving robot in the ideal circumstance not have enough kinetic energy to step forward. The CGS control method we proposed is feasible and requires less energy than the existing control method. This method ensures the proposed model will not rub with the ground based on the elastic coefficient of the ground.

References

[1] Hirose, M. , & Ogawa, K. . (2007). Honda humanoid robots development. Philosophical Transactions, 365(1850), 11-19.

[2] Campos-Macias, L. , Carbajal-Espinosa, O. , Loukianov, A. , & Bayro-Corrochano, E. . (2017). Stabilization method for dynamic gait in bipedal walking robots. 2016 IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids). IEEE.

[3] Kuindersma, S. , Deits, R. , & Fallon, M. . (2016). Optimization-based locomotion planning, estimation, and control design for atlas. Autonomous Robots, 40(3), 429-455.

[4] DA Winter. (1995). Human balance and posture control during standing and walking. Gait & Posture, 3(4), 193-214.

[5] Anderson, F. C. , & Pandy, M. G. . (2001). Dynamic optimization of human walking. Journal of Biomechanical Engineering, 123(5), 381.

[6] CE Bauby, & Kuo, A. D. . (2000). Active control of lateral balance in human walking. Journal of Biomechanics, 33(11), 1433-1440

[7] MCGEER T. Passive dynamic walking[J]. International Journal of Robotics Research, 1990, 9(2): 62 – 82.

[8] MCGEER T. Passive walking with knees[C]//Proceedings of IEEE International Conference on Robotics and Automation. Cincinnati: Anon, 1990: 1640 – 1645.

[9] Goswami, & Ambarish. (1998). A study of the passive gait of a compass-like biped robot: symmetry and chaos. International Journal of Robotics Research.

[10] Mariano, Garcia, Anindya, Chatterjee, Andy, & Ruina, et al. (1998). The simplest walking model: stability, complexity, and scaling. Journal of Biomechanical Engineering, 120(2), 281-288.

[11] J. Moon and M. W. Spong, "Bifurcations and chaos in passive walking of a compass-gait biped with asymmetries," 2010 IEEE International Conference on Robotics and Automation, 2010, pp. 1721-1726, doi: 10.1109/ROBOT.2010.5509856.

[12] Gritli, H., & Belghith, S. . (2016). Walking dynamics of the passive compass-gait model under ogy-based control: emergence of bifurcations and chaos. Communications in Nonlinear Science & Numerical Simulation, 47, 308-327.

[13] Gritli, H. , & Belghith, S. . (2017). Walking dynamics of the passive compass-gait model under ogy-based state-feedback control: analysis of local bifurcations via the hybrid poincaré map. Chaos Solitons & Fractals, 98, 72-87.

[14] Gritli, H. , & Belghith, S. . (2018). Walking dynamics of the passive compass-gait model under ogy-based state-feedback control: rise of the neimark–sacker bifurcation. Chaos Solitons & Fractals, 110, 158-168.

[15] Wafa Znegui, Hassène Gritli, Safya Belghith,Design of an explicit expression of the Poincaré map for the passive dynamic walking of the compass-gait biped model,Chaos, Solitons &

Fractals,Volume 130,2020
[16] Znegui, W. , Gritli, H. , & Belghith, S. . (2020). Control of the Passive-Dynamic Locomotion of the Compass-Gait Biped Robot. 2020 4th International Conference on Advanced Systems and Emergent Technologies (IC_ASET).
[17] Gritli, H. , Khraeif, N. , & Belghith, S. . (2011). Falling of a passive compass-gait biped robot caused by a boundary crisis. Proceedings of the 4th Chaotic Modeling and Simulation International Conference Crete, Greece.
[18] Gritli, H. , Khraeif, N. , & Belghith, S. . (2013). Chaos control in passive walking dynamics of a compass-gait model. Communications in Nonlinear ence and Numerical Simulation, 18(8), 2048–2065.
[19] N. Khraief, N. K. M'Sirdi and M. W. Spong, "Nearly passive dynamic walking of a biped robot," 2003 European Control Conference (ECC), 2003, pp. 1832-1838, doi: 10.23919/ECC.2003.7085232.
[20] F. Asano and Z. -w. Luo, "On Energy-Efficient and High-Speed Dynamic Biped Locomotion with Semicircular Feet," 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2006, pp. 5901-5906, doi: 10.1109/IROS.2006.282470.
[21] Montazeri Moghadam, Saeed & Sadeghi, Maryam & Niaty, Ali & Towhidkhah, Farzad & Jafari, Sajad. (2018). The simple chaotic model of passive dynamic walking. Nonlinear Dynamics. 93. 10.1007/s11071-018-4252-8.
[22] Gritli, H. , Belghith, S. , & Khraief, N. . (2015). Ogy-based control of chaos in semi-passive dynamic walking of a torso-driven biped robot. Nonlinear Dynamics, 79(2), 1363-1384.
[23] Maysam, F. , Sajjad, T. , & Hossein, M. . (2018). Analyzing bifurcation, stability and chaos for a passive walking biped model with a sole foot. International Journal of Bifurcation and Chaos, 28(09), 1850113.
[24] Kurz, M. J. , & Stergiou, N. . (2007). Hip actuations can be used to control bifurcations and chaos in a passive dynamic walking model. J Biomech Eng, 129(2), 216-222.
[25] Zhu, Y. . (2010). Simulation and analysis of simple biped passive dynamic walking model. Journal of Harbin Institute of Technology.
[26] Mizuno, M. , Ohtake, H. , Tanaka, K. , & Wang, H. O. . (2008). Passive dynamic walking with elastic energy. Transactions of the Society of Instrument and Control Engineers, 43(11).
[27] Gritli, H. , & Belghith, S. . (2016). Bifurcations and chaos in the semi-passive bipedal dynamic walking model under a modified ogy-based control approach. Nonlinear Dynamics, 83(4), 1955-1973.
[28] Gritli, H. , & Belghith, S. . (2016). Displayed phenomena in the semi-passive torso-driven biped model under ogy-based control method: birth of a torus bifurcation. Applied Mathematical Modelling, 40(4), 2946-2967.
[29] Gritli, H. , & Belghith, S. . (2018). Walking dynamics of the passive compass-gait model under ogy-based state-feedback control: rise of the neimark–sacker bifurcation. Chaos Solitons & Fractals, 110, 158-168.
[30] Goswami, B. Espiau and A. Keramane, "Limit cycles and their stability in a passive bipedal gait," Proceedings of IEEE International Conference on Robotics and Automation, 1996, pp. 246-251 vol.1, doi: 10.1109/ROBOT.1996.503785.
[31] R. P. Kumar, J. -. Yoon and G. -. Kim, "Simplest dynamic walking model with toed feet," Humanoids 2008 - 8th IEEE-RAS International Conference on Humanoid Robots, 2008, pp. 245-250, doi: 10.1109/ICHR.2008.4755952.
[32] T. McGeer, "Passive walking with knees," Proceedings., IEEE International Conference on Robotics and Automation, 1990, pp. 1640-1645 vol.3, doi: 10.1109/ROBOT.1990.126245.
[33] Wu, Y. , Yao, D. , & Xiao, X. . (2018). The effects of ground compliance on flexible planar passive biped dynamic walking. Journal of Mechanical Science & Technology, 32(4), 1793-1804.