PID CONTROLLER IN STEP-MOTION CONTROL FOR BIPEDAL ROBOT WITH ELASTIC LEGS

ĐIỀU KHIỂN PID CHO BƯỚC ĐI CỦA BIPEDAL ROBOT VỚI CHÂN DẺO

[1]Tran Hoang Chinh, [1]Nguyen Minh Tam, [1]Le Thi Thanh Hoang, [2]Nguyen Thien Van, [3]Mircea Ivanescu, [1]Nguyen Van Dong Hai

[1] Ho Chi Minh city University of Technology and Education (HCMUTE), Vietnam
[2]Universitatea Politehnica din Bucuresti (UPB), Romania
[3]Universitatea din Craiova (UCV), Romania

Received 29/01/2018, Peer reviewed 20/3/2018, Accepted for publication 9/7/2018

ABSTRACT

The bipedal robot is a similar model in robot control problems. Former researches mostly focused on bipedal robots that only have solid links. This action limits the flexibility in the mechanical structure of the system. In order to make a robot more flexible, some researcher suggested replacing the solid legs with compliant components such as elastic legs. Basing on that transforming in mechanical structure, many control algorithms have been implemented by the direction that approximating robot into SLIP model to simplify the real model. Then, conventional control algorithms such as PID, sliding mode are respectively used to step-motion control for a robot. However, this approximation makes the robot control not exact because the approximated model and real model are not completely the same. In this paper, dynamic equations of an elastic bipedal robot are analyzed and a popular control algorithm –PID- is utilized on a real model which is not approximated. Control results are proved to be acceptable through simulation in Matlab/Simulink.

Keywords: *bipedal robot; elastic legs; compliant component; SLIP model; PID control; sliding mode control.*

TÓM TẮT

Robot di chuyển bằng hai chân (bipedal robot) là một đối tượng quen thuộc trong vấn đề điều khiển robot. Các nghiên cứu trước đây đa phần đều khảo sát robot hai chân với các link cứng. Điều này hạn chế sự linh động về cơ khí của hệ thống. Để bipedal robot đáp ứng linh động hơn, một số nghiên cứu đã đề nghị thay đôi chân bằng chất liệu đàn hồi như chân dẻo. Tương ứng với sự thay đổi kết cấu cơ khí trên, nhiều giải thuật điều khiển được thực hiện và phát triển đi theo hướng tiếp cận việc xấp xỉ robot về dạng mô hình SLIP để đơn giản hóa. Sau đó, các giải thuật thông thường như PID, trượt được lần lượt áp dụng để điều khiển sự di chuyển của robot. Tuy nhiên, việc xấp xỉ này làm sự điều khiển robot không còn chính xác vì đối tượng xấp xỉ không hoàn toàn giống với hệ thống. Trong bài báo này, phương trình toán học của robot có đôi chân dẻo được phân tích và một giải thuật thông thường là PID được áp dụng trực tiếp lên mô hình chưa được xấp xỉ. Kết quả điều khiển là chấp nhận được thông qua các kết quả mô phỏng Matlab/Simulink.

Từ khóa: *robot hai chân; chân dẻo; chất liệu đàn hồi; mô hình SLIP; điều khiển PID; điều khiển trượt.*

1. INTRODUCTION

A bipedal robot is a popular model in robot control problems with first beginning with a robot with only solid links [1]-[3]. The motion of a robot is slow and inflexible. An effective method for this kind of robot used to be ZMP method [4], [5]. Some compliant components were added to make the motion more fast and flexible [6]-[9]. Due to the complicated structure of the multi-link robot as a bipedal robot, SLIP model has been usually used to simplify the real model of this kind of robot [10], [11]. With this simplified model, potential energy and kinematic energy of bipedal robot can be examined. When considering bipedal types of robot, SLIP-model regards robot as a remarkable body with two different massless legs which have stiffness coefficient. In this case, when one leg is in the stance phase, the other leg is in the flight phase.

In those researches, only the SLIP approximated model is used in a simulation. This action can make the success in simulation does not actually perform well in an adequate model. In [12], hierarchical sliding mode control (HSMC) was used successfully on athlete robot (AR). But, with the complicated structure of the controller, and the acceptable simulation results, HSMC needs to be improved. Then, a set of simple PID controllers is used in this paper to control the whole robot. Because PID controller is simple in structure, it is easier to be embed into a microprocessor with less resource requirement than by complex nonlinear or intelligent controller. Otherwise, nonlinear controller, such as sliding mode control, requires the exact nonlinear equations of the system. This difficulty causes the nonlinear controller not to be flexible in controlling a complicated model like a two-legged robot with elastic legs. Thence, PID controller is a more simple method which is suggested to be used for the robot which has AR-form in this paper. The simulation results are the faster adaptive response of the robot.

This paper concludes of four sections. The introduction is inferred in section I. Dynamic equations of the bipedal robot with elastic legs is shown in section II. Then, PID controller and simulation is introduced in section III. Conclusion in section IV ends the paper.

2. DYNAMIC EQUATION

2.1 Mathematical Modelling

Robot with compliant legs in this paper can be inferred to athlete robot, which was first created by Ryuma [13], [14] in University of Tokyo (Figure 2). This is a combination between two-legged robot with the elastic leg for disabled people Figure 1, Figure 2.

Table 1. *Important points of AR*

Element	Description
C_j	mass center of link j (j=1, 5)
O_j	with (j=1, 2, 3, 4) connecting point of link j and link j+1
A_j	center of the curved part of elastic leg (j=1, 5).
D_j, E_j	two edge points of elastic legs with coordinates: (x_{Dj},y_{Dj}) and (x_{Ej},y_{Ej}) (j=1, 5).
F_j	middle point of flexible part which has co-ordinate as (x_{Fj},y_{Fj}) (j=1,5).
$\beta = E_j A_j C_j$	Angle of curved part of elastic parts

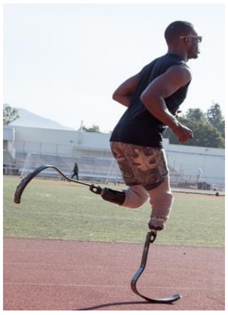

Figure 1. *Motion of disabled people with elastic legs*

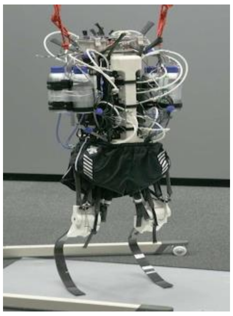

Figure 2. *AR - University of Tokyo*

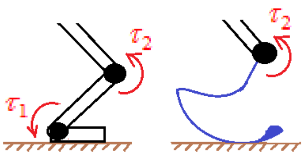

Figure 3. *Correlation between leg of solid robot and AR*

Two lowest links of AR are elastic. These links keep robot moving flexibly and storing elastic potential energy in each step. It is necessary to model AR into an appropriate and simple form. Due to [12], an elastic leg can be considered as in Figure 4. In this opinion, the elastic leg can self-balance at vertical direction. The important points are listed in Table 1.

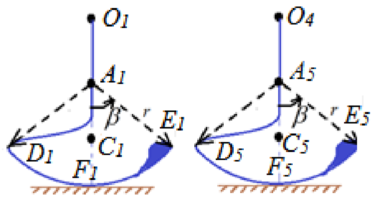

Figure 4. *Self-balancing position of elastic legs*

Under this design, an AR can be described in a mathematical model as in Figure 5. When no force effects, the elastic leg can self-balance as in Figure 4. These legs also accumulate elastic energy is also accumulated by these leg for motion. Model of AR can be described as:

- There are five links: link 2, 3, 4 are solid. Link 1, 5 are elastic.
- Except for link 1, another link has a motor to control motion. These motion also affect indirectly the link 1.
- Link 2, 4 have the same mass. But this link should have insignificant mass, compared to link 3.The length of link 3 is zero.

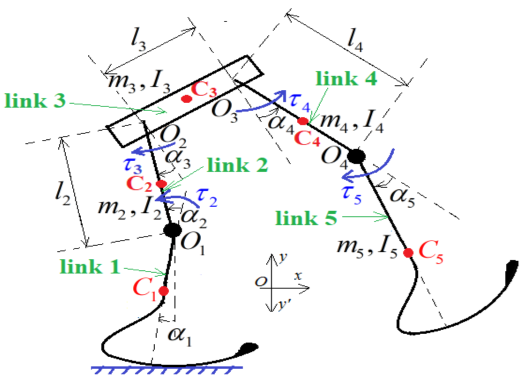

Figure 5. *Mathematical model of AR*

Table 2. *Parameters of AR*

Parameters	Unit	Description
m_j	kg	The mass of the link j (j=1, 2, 3, 4, 5); m_1=m_5; m_2=m_4
L_j	m	Length of link j (j=2, 3, 4); l_2=l_4; l_3=0
α_1	rad	Angle between vertical axis with link 1 and $\alpha_1 = C_1O_1y'$
α_j	rad	Angle between link j with link j-1 (j=2, 3, 4, 5)
I_j	kgm^2	Inertial moment of link j
R	m	Radius of curved part of link 1 and 5
ξ	Nm/rad	Rotational spring coefficient

2.2 Dynamic equation generation [12]

Castigliano's Theorem has provided a good tool for forces analyzation on curved components. AR can be considered as an equivalent inverted pendulum and elastic legs are equivalent to springs. Consider force which created by rotational spring in Figure 6b is much remarkable than the force which created by linear spring in Figure 6a.

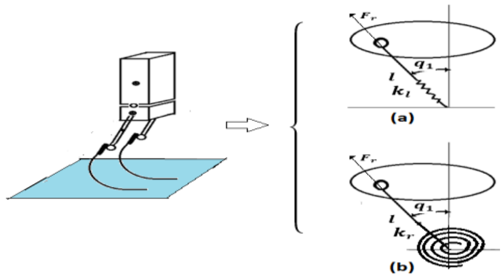

Figure 6. *Equivalent IP model of robot with compliant leg, where:*

a/ linear spring *b/rotational spring*

Then, strain potential energy of AR can be defined as:

$$P_{strain} = \xi\alpha_1^2/2 \quad (1)$$

Correspondingly, total potential and kinetic energy are

$$P = P_{strain} + \sum_{k=1}^{5} m_k g y_{Ck} \quad (2)$$

$$K = \sum_{k=1}^{5}\left[I_k\dot{\alpha}_k^2 + m_i\left(\dot{x}_{Ck}^2 + \dot{y}_{Ck}^2\right)\right]\Big/2 \quad (3)$$

Lagrange operator is:

L = K – P (4)

Dynamic equations generalized by Euler-Lagrange method are obtained

$$\frac{\partial L}{\partial \alpha_1} - \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\alpha}_1}\right) = 0 \quad (5)$$

$$\frac{\partial L}{\partial \alpha_k} - \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\alpha}_k}\right) = 0 \ \ (k=2, 3, 4, 5) \quad (6)$$

Define $\alpha = [\alpha_1 \ \alpha_2 \ \cdots \ \alpha_5]^T$, $\tau = [0 \ \tau_2 \ \tau_3 \ \tau_4 \ \tau_5]^T$. After calculations from (5), (6), matrix form of dynamic equations is

$$A(\alpha_k)\ddot{\alpha} = B(\alpha_k, \dot{\alpha}_k) + \tau \text{ (k=2, 3, 4, 5)} \quad (7)$$

$$\text{or} \quad \ddot{\alpha} = A^{-1}(\alpha_k)\tau + A^{-1}(\alpha_k)B(\alpha_k, \dot{\alpha}_k) \quad (8)$$

(k=2, 3, 4, 5)

The order of AR is five (there are five variables in (8)). Thence, calculating directly A^{-1}, $A^{-1}B$ to get exact formula is impossible (Matlab/Simulink window can just allow 25000 characters to appear). Flow-chart in Figure 7 describes the process of simulation when there is not the formula of dynamic equations of the system. The sample-time, in this case, can be chosen as 0.01s. Variables β_i can be calculated by α_i from (9) below

$$\beta_1 = \alpha_1; \ \ \beta_2 = \beta_1 - \alpha_2; \ \ \beta_3 = \alpha_3 - \beta_2; \quad (9)$$
$$\beta_4 = -\beta_3 - \alpha_4; \ \ \beta_5 = \beta_4 + \alpha_5$$

Similarly, α_i can be calculated by β_i from formulas in (10)

$$\alpha_1 = \beta_1; \ \ \alpha_2 = \beta_1 - \beta_2; \ \ \alpha_3 = \beta_2 + \beta_3; \quad (10)$$
$$\alpha_4 = -\beta_3 - \beta_4; \ \ \alpha_5 = \beta_5 - \beta_4$$

Definition of variables in (8) makes dynamic equations easier to be obtained. But, the observability of designing trajectories for the motion of AR becomes more difficult. Then, from, a transformation of variables is suggested in formulas (9) and (10). The motion of a step must be chosen as that before finishing a step, one leg must always touch the ground and another leg must be off the ground. The condition of two legs will be the same after a period of step with the changing condition of two legs.

Consider α_{id} and β_{id} as reference signals of α_i and β_i. When leg 1 and 2 touch the ground, angle $\beta_0 = const > 0$ describes the error between the vertical axis and one leg as in Figure 9. And T is the defined the time to finish a step in Figure 10 of AR.

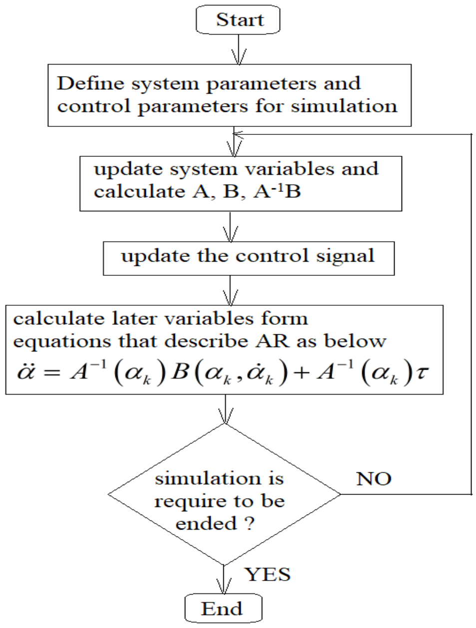

Figure 7. *Simulation process*

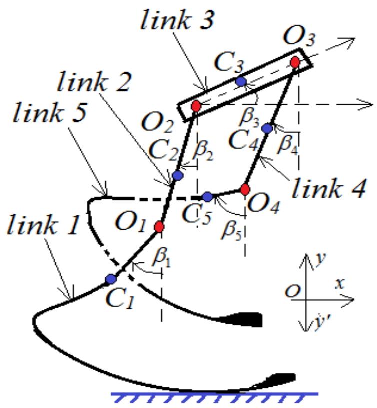

Figure 8. *Model structure when transforming former variables α_i in (8) with new variables β_i*

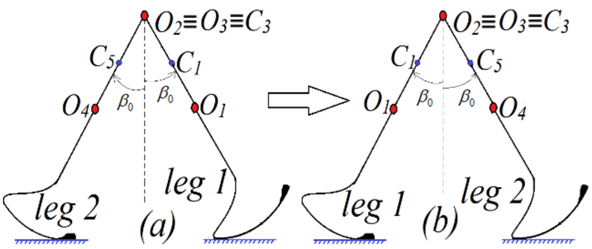

Figure 9*. Process of a step*

a) Beginning a step b) Finishing a step

Many studies [15], [16] presents different methods of designing oscillators for walking motion of a two-legged robot. Anyway, these methods are complicated and based on intuition and developed through simulations and experiments. In this thesis, a trajectory of legs are designed.

We consider

$\beta_{1d} = \beta_0 = const$, $\beta_{2d} = \beta_0 = const$, $\beta_{3d} = 0$, β_{4d} , β_{5d} as the reference trajectories of β_1, β_2, β_3, β_4, β_5. (11)

Figure 10 below describes the trajectories β_{4d}, β_{5d}

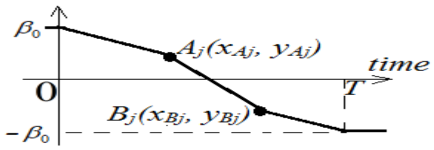

Figure 10. *Trajectories* β_{jd} $(j = 4,5)$

Co-ordinates (x_{Aj}, y_{Aj}) and (x_{Bj}, y_{Bj}) of A_i and B_i have to be selected through genetic algorithm.

3. PID CONTROLLER

PID is a SISO control algorithm. But, AR is a MIMO under-actuated nonlinear system. Therefore, a structure is suggested as in Figure 11 below. System parameters for simulating system are selected as:

$\gamma_1 = 10^{-1}(m)$; $\gamma_2 = 1(m)$; $r = 0.2(m)$; $\gamma_3 = r - \gamma_1$; $\gamma_4 = \gamma_2 - r$; $m_1 = 10^{-2}(kg)$; $m_2 = 10^{-1}(kg)$; $m_3 = 0.5(kg)$; $I_1 = 10^{-3}(kgm^2)$; $I_2 = 2\times10^{-2}(kgm^2)$; $I_3 = 10^{-1}(kgm^2)$; $l_3 = 0(m)$; $l_2 = 0.7(m)$; $g = 9.81(N/kgm^2)$; $k = 0.2(N/kgm^2)$; $T = 1.01(s)$; $q_0 = \pi/8(rad)$. (12)

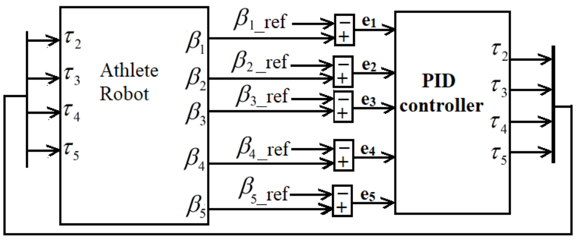

Figure 11. *Structure of PID controller for step motion of AR*

Peirodic time T, co-ordinates of points A_j, B_j in *Figure 10*, and controller parameters of PID controller is calculated by GA program with the process below

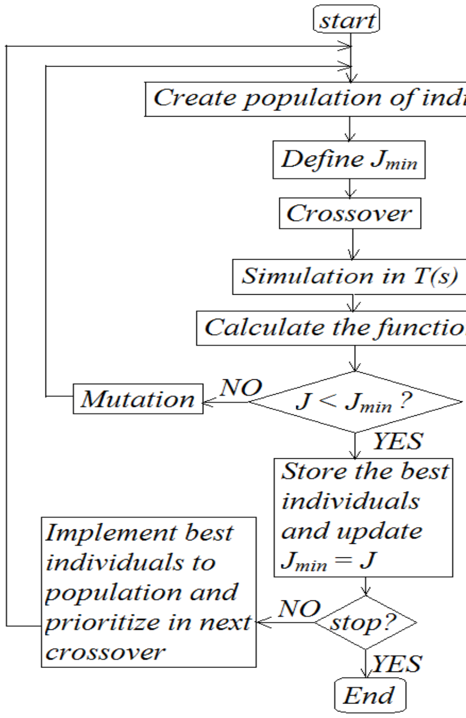

Figure 12. *GA process*

Fitness function is (best individuals have smallest J) below:

$$J = \left[\sum_{j=1}^{n} \sum_{i=k}^{5} \zeta_k^2 \right] \Big/ T \tag{13}$$

where:

$\zeta_k = \beta_k - \beta_{dk}$ is the error of real angle β_k and designed trajectory β_{dk} in Figure 8. *T* is periodic time of a step-motion. *n* is the quantity of sample in time *T*.

In the GA program, periodic time T, coordinates of points A_j, B_j and controller parameters of PID controller are transformed into chromosomes of individuals. Then, random couples are selected for crossover process. Best individuals are chosen (through fitness function J which is calculated in (13). After a suitable time running computer, GA gives the best results until that time.

There are different ways to design the output signals of PID controller under the errors-input signals. Two cases can be examined as follows:

Case 1:

Control signals are designed as below:

$$\tau_2 = K_1 e_2 + K_2 \dot{e}_2 \;;\quad \tau_3 = K_3 e_3 + K_4 \dot{e}_3 \;;$$
$$\tau_4 = K_{p4} e_4;\;\; \tau_5 = K_{p5} e_5 \qquad (14)$$

In this design, link 4, 5 is controlled by P-controllers. Using only P-controllers keep the number of control parameters small enough for the searching algorithm to work efficiently. Link 2 and 3 are correspondingly controlled by PD-controller.

With system parameters are selected in (14), by using GA in searching trajectory and control parameters, results are found as below:

T=0.79;K1=219.1;K2 =2.59;

K3=84.4;K4=0.28; (15)

Kp4=66.7;Kp5=24.8;

$y_{A4} = -1.1561$; $x_{A4} = 0.3635$;

$y_{B4} = -1.6085$; $x_{A4} = 0.6479$;

$y_{A5} = 0.9802$; $x_{A5} = 0.1739$;

$y_{B5} = -1.4326$; $x_{B5} = 0.3003$

Simulation results of step-motion under PID controller which is described in (12) is listed in Figure 13 to Figure 18.

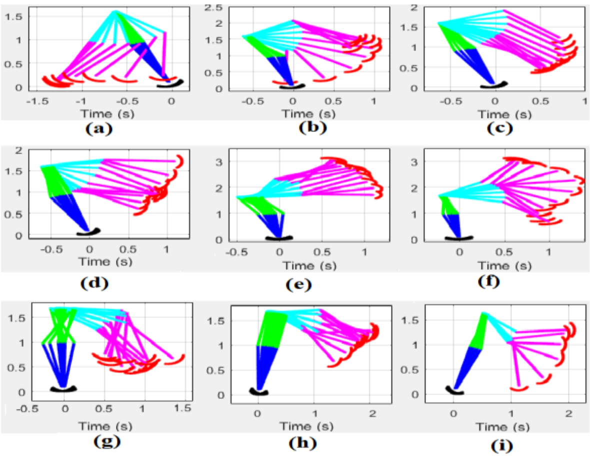

***Figure 13.** Motion of AR*

a) From 0s to 0.1s

b) From 0.1s to 0.2s

c) From 0.2s to 0.3s

d) From 0.3s to 0.4s

e) From 0.4s to 0.5s

f) From 0.5s to 0.6s

g) From 0.6s to 0.7s

h) From 0.7s to 0.8s

i) From 0.8s to 0.85s

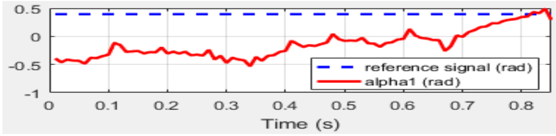

***Figure 14.** Trajectory of* α_1 *(rad)*

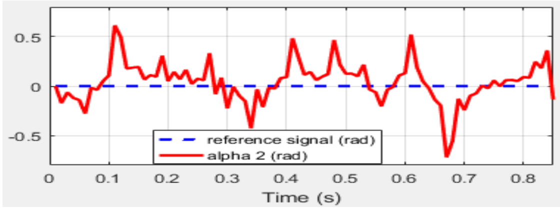

***Figure 15.** Trajectory of* α_2 *(rad)*

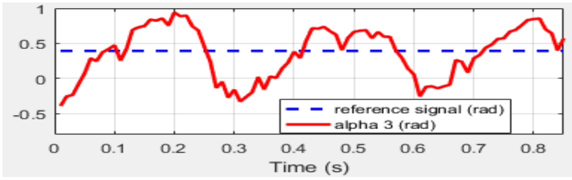

***Figure 16.** Trajectory of* α_3 *(rad)*

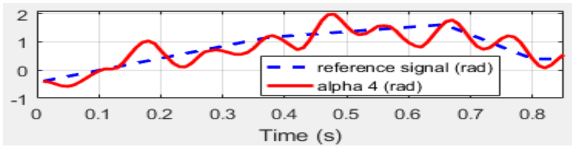

***Figure 17.** Trajectory of* α_4 *(rad)*

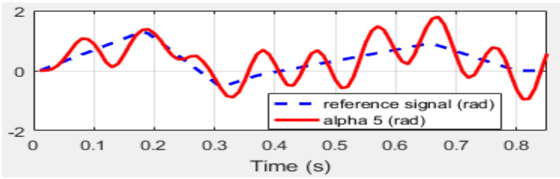

***Figure 18.** Trajectory of* α_5 *(rad)*

In case one, the controller PID as in (12), robot finish a step in 0.85s. Motion process is described in Figure 13. The trajectory of each link, which is defined in Figure 5, in inferred from Figure 14 to Figure 18. The higher order link is controlled well (link 5) because it is directly controlled by a P-controller. The effect of other controller and another lower-order link (link 1, 2...) is not considerable. Vice versa, the vibration of link is bigger with the lower-order links. No controller in link 1 cause the vibration much in link 1. Otherwise, the controller is randomly selected through GA causes an acceptable set of controller parameters that make robot finish a step-motion.

Case 2:

Control signals are designed as

$$\tau_2 = K_1 e_1 + K_2 \dot{e}_1 + K_3 e_2 + K_4 \dot{e}_2;$$
$$\tau_3 = K_{p3} e_3;\ \ \tau_4 = K_{p4} e_4;\ \ \tau_5 = K_{p5} e_5 \qquad (16)$$

In this design, link 3, 4, 5 is controlled by P-controllers. Using only P-controllers keep the number of control parameters small enough for the searching algorithm to work efficiently. Link 1 and 2 are controlled by a combination of two PD-controllers.

With system parameters are selected in (12), by using GA, the trajectory and control parameters are found as below:

T=0.64; K1=-75.5; K2=-8.2;
K3=327.2; K4=5.06;
Kp3=75.0001; Kp4=45.5001;
Kp5=82.3001; $y_{A4} = -1.3069$;
$x_{A4} = 0.1857$; $y_{B4} = -1.8598$; (17)
$x_{A4} = 0.5761$; $y_{A5} = 1.0053$;
$x_{A5} = 0.0961$; $y_{B5} = -1.5331$;
$x_{B5} = 0.4289$

Simulation results of step-motion under PID controller which is described in (18) is listed from below:

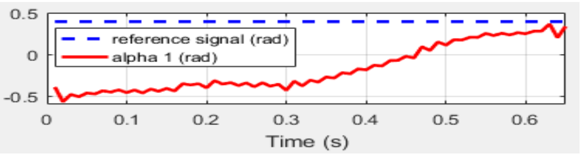

Figure 19. *Trajectory of* α_1 *(rad)*

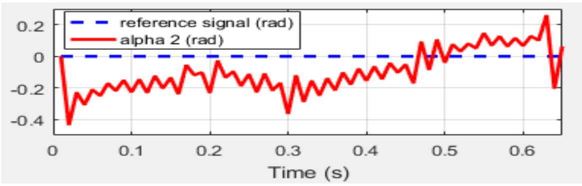

Figure 20. *Trajectory of* α_2 *(rad)*

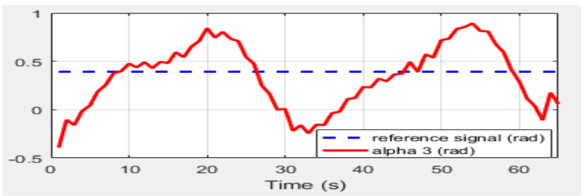

Figure 21. *Trajectory of* α_3 *(rad)*

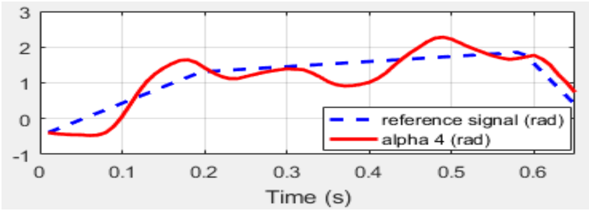

Figure 22. *Trajectory of* α_4 *(rad)*

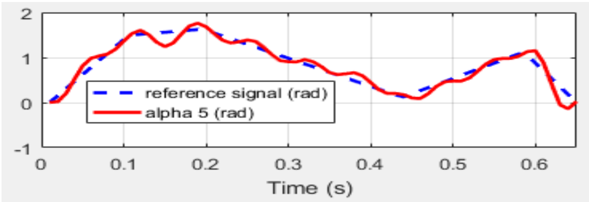

Figure 23. *Trajectory of* α_5 *(rad)*

The result of the robot step in case 2 is the same as in case 1: higher-order links track the trajectories better than the lower-order link. In this case, GA(18) finds a better set that finishes step of the robot in 0.65s. PID controller in case 2 that also controller link 1 and 2 by a single signal control (differently from case 1, link 1 is also controlled in case 2). The results are better, in both tracking error and settling time.

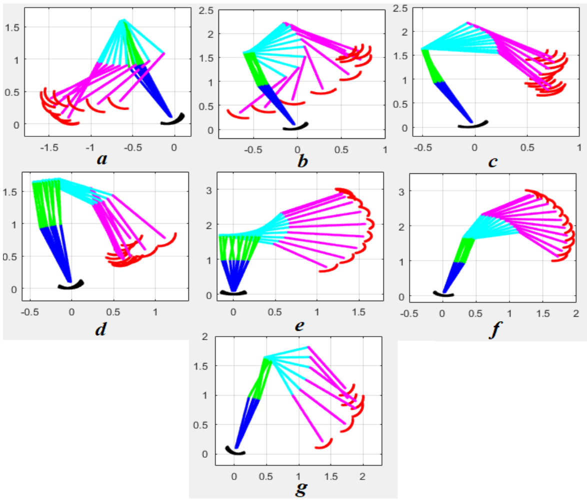

Figure 24. *Motion of AR*

a) From 0s to 0.1s
b) From 0.1s to 0.2s
c) From 0.2s to 0.3s
d) From 0.3s to 0.4s
e) From 0.4s to 0.5s
f) From 0.5s to 0.6s
g) From 0.6s to 0.65s

4. CONCLUSION

In both case, from simulation results, time to finish a step for AR is just only 0.65s and 0.85s, faster than in HSMC controller of [12]. Also, the structure of the controller is more simple. The using of HSMC controller is not necessary to control this kind of robot due to its complex structure. So many parameters have to be recognized. Therefore, with fewer parameters and simple structure, PID controller is suitable to be applied on this kind of robot.

ACKNOWLEDGMENT

By the help in feedback of Prof. Mircea Nitulescu and Prof. Ionel Cristian Vladu- faculty of automation, electronics and computer, University of Craiova, this dedication is completed. Therefore, the authors are very grateful to these supports and thanks should be given to them from the authors.

REFERENCE

[1] Patrick M. Wensing and David E. Orin, *Control of Humanoid Hopping Based on a SLIP Model,* Advances in Mechanisms, Robotics and Design Education and Research, Part of the Mechanisms and Machine Science book series, pp. 265-274, Springer, 2013.

[2] Farley, C. T., Glasheen, J. And Mcmahon, T. A, *Running springs – speed and animal size*, The Journal of Experimental Biology, 185, pp. 71-86, 1993.

[3] Full, R. J. and Koditschek, D. E, *Templates and anchors: neuromechanical hypotheses of legged locomotion on land*, Journal of Experimental Biology, 202(23):3325–3332, 1999.

[4] Qinghua, L., Takanishi, A. & Kato, I, *A Biped Walking Robot having a ZMP Measurement System using Universal Force-moment Sensors*, In Proceeding of Intelligent Robots and System, pp. 1568-1573, IEEE, 1991.

[5] Napoleon, Shigeki, N. & Mitsuji, S, Balance Control Analysis of Humanoid Robot based on ZMP Feedback Control, *Proceedings of International Conference on Intelligent Robots and Systems,* pp. 2437-2442, IEEE, 2002.

[6] J. A. Smith & A. Seyfarth, *Elastic Leg Function in a Bipedal Walking Robot,* Journal of Biomechanics, Page S306, Vol. 40, Supplement 2, Elsevier, 2007.

[7] Fumiya Iida, Yohei Minekawa, Jurgen Rummel, *Andre Seyfarth, Toward a human-like biped robot with compliant legs*, Journal of Robotics and Autonomous Systems, Vol. 57, Issue 2, pp. 139-144. Elsevier, 2009.

[8] Chen Koo Toh, Ming Xie, Hejin Yang, Guoqing Zhang, Quoc Phuong Bui & BoTian, *Flexible Foot Design for Biped Walking on Uneven Terrain*, In Proceeding of International Conference on Intelligent Robotics and Applications (ICIRA 2010), Part of the Lecture Notes in Computer Science book series (LNCS, Vol. 6424), pp. 442-452. Springer, 2010.

[9] Byoung-Ho Kim, *Work Analysis of Compliant Leg Mechanism for Bipedal Walking Robots*, International Journal of Advanced Robotic Systems, Vol. 10, 334:2013, 2013.

[10] Gianluca Garofalo, Christian Ott & Alin Albu-Schaffer, "Walking control of fully actuated robots based the Bipedal SLIP model", In *Proceeding of International Conference on Robotics and Automation (ICRA)*, pp. 1456-1463. IEEE, 2012.

[11] Yiping Liu, Patrick M. Wensing, David E. Orin & Yuan F. Zheng, *Dynamic walking in a humanoid robot based in 3D Actuated Dual-SLIP model,* In *Proceeding of International Conference on Robotics and Automation (ICRA)*, pp. 5710-5717, 2015.

[12] Nguyen Van Dong Hai, Huynh Xuan Dung, Nguyen Minh Tam, Ionel Cristian Vladu, Mircea Ivanescu, *Hierarchical Sliding Mode Algorithm for Athlete Robot Walking*, Journal of Robotics, Article ID 6348980, Hindawi, December-2017.

[13] Ryuma Niiyama, Satoshi Nishikawa, Yasuo Kuniyoshi, *Biomechanical Approach to Open-Loop Bipedal Running with a Musculoskeletal Athlete Robot*, Journal of Advanced Robotics, Vol. 26, Issue. 3-4, 2012.

[14] Ryuma Niiyama and Yasuo Kuniyoshi, *Design of a Musculoskeletal Athlete Robot: A Biomachanical Approach*, Proceedings of the Twelfth International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines, Turkey, 2009.

[15] Endo, G., Morimoto, J., Nakanishi, J. & Cheng, G, *An Empirical Exploration of a Neural Oscillator for Biped Locomotion Control*, In Proceedings of International Conference on Robotics & Automation, pp. 3036-3042. IEEE, 2004.

[16] Zielinska, T, *Gait Rhythm Generators of a Two Legged Walking Machine,* ROMANSY 11, Series of International Centre for Mechanical Sciences, Vol. 318, pp. 165-171. Springer, 1997.

Corresponding author:
Nguyen Van Dong Hai
Ho Chi Minh city University of Technology and Education (HCMUTE)
Email: hainvd@hcmute.edu.vn