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Stabilization of Biped Trunk in the Presense of Hip Motion Disturbance Using a Fuzzy-PID Controller

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***Abstract*— Analysis of human gait is demonstrated that the movement of the hip is constrained in a sinusoidal path. In this paper, biped trunk oscillation in the presence of hip motion disturbance is approximated by a nonlinear inverted pendulum model. Then, the Biped trunk by torque hip control is stabilized using Fuzzy-PID control technique. In the torque control system, PID gains can be adjusted online by the fuzzy logic in accordance to the variation of inputs to stabilize the oscillation angle of the trunk. In order to investigate the performance of the proposed controller, the simulation results are compared with PID Controller tuned on Ziegler-Nichols method. In addition to, the robustness of proposed controllers is investigated by imposing disturbance in process. It can be seen that proposed control method has fast response, low overshoot and error, better tracking performance and strong robustness.**

Keywords—biped trunk, Fuzzy-PID controller, hip motion disturbance, sinusoidal path.

I. Introduction

Generally, an inverted pendulum is considered as dynamic walking models. In this paper, the hip is constrained to move along an arc during walking [1]. In fact, it can be assumed the hip joint of a biped robot is constrained in a sinusoidal path and center of mass (COM) of biped trunk swings around of hip. Furthermore, an inverted pendulum can be used to represent the biped trunk motion on hip disturbance. The balancing of an upper body of biped dynamic is a research topic so that there are some strategies employed for biped trunk stabilization. The major challenge is that stabilization of upper limb during walking must be guaranteed, while at during walking step, each leg swing to forward position. In [2], [3], many methods are introduced, in which the biped trunk is simulated as an inverted pendulum. Another way to balance biped trunk in walking is a Zero Moment Point (ZMP) criterion. In [4] a learning control method based on ZMP is presented to compensate a torso of a biped. Based on the ZMP technique, the center of mass of body trunk should not exist inside the support polygon that the contact surface of the feet and ground is formed it. In [5], a novel technique to stable a torso of a biped system is introduced. In this paper, a simple model of a biped is represented to study how the torso stabilizes during motion. In [6], a controller algorithm for the biped torso spring inverted pendulum is presented. The inverted pendulum is consisted of springy legs and the pointed trunk. This concept could be a framework for trunk motion stability and hip in biped locomotion. In the most common configuration of inverted pendulum control, the cart moves along a horizontal path. While the special research in which the cart moves on a curved path less has been considered. In [7], stabilization for an inverted pendulum on a gharry, which travels along an arc path in the horizontal-vertical plane, is discussed. In this paper, biped trunk motion in the presence of hip motion disturbances caused by hip displacement of biped is approximated by an inverted pendulum model that travels along a sinusoidal path. In this paper, a Fuzzy-PID controller is proposed to improve the controller performance. A Fuzzy-PID control method has a robust performance against on external disturbances [8], [9]. In addition, the proposed control is compared to the PID method. This paper categorized as follows: in section II, the mathematical modeling of inverted pendulum motion on a curved path is constructed. The control system for the biped trunk are described in section III, and simulation results of proposed controllers under disturbance are discussed in IV .Finally, in section IV , the conclusions of this research are given.

II. Dynamic Modeling

In this study, a nonlinear inverted pendulum model is used to approximate the biped trunk as shown in Fig. 1. Let we consider the COM of the trunk with a mass connected by a massless rod of length to hip with a mass that moves on a sinusoidal path and the system moves by applying torque input on the hip as well.

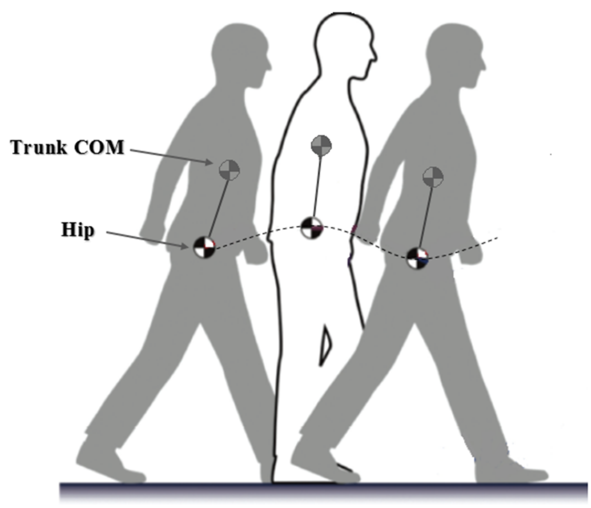

Fig. 1. The position of trunk COM and hip in human gait

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The equations of motion of this system are derived by Lagrange method as given [10]:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right)-\frac{\partial L}{\partial \theta}=Q \tag{1}$$

Where $L=T-V$ is a Lagrange form, Q is generalized momentum acting in the direction of θ angle, T is kinetic energy and also V is potential energy. The absolute velocity of the hip is yield as:

$$\vec{V}_M=\dot{x}i+\dot{y}j \tag{2}$$

By derivative from y=sin(x) we have:

$$\vec{V}_M=\dot{x}i+\dot{x}\cos(x)j \tag{3}$$

In addition, the absolute velocity of the trunk COM is yield as:

$$\vec{V}_m=\left(\dot{x}+l\dot{\theta}\cos(\theta)\right)i+(\dot{x}\cos(x)-l\dot{\theta}\sin(\theta))j \tag{4}$$

The energies of the system are the sum of the kinetic energy and the potential energy of the hip and trunk as following:

$$T=\frac{1}{2}M\dot{x}^2(1+\cos^2(x))+\frac{1}{2}m((\dot{x}+l\dot{\theta}\cos(\theta))^2+(\dot{x}\cos(x)-l\dot{\theta}\sin(\theta))^2) \tag{5}$$

$$V=Mg\sin(x)+mg(l\cos(\theta)+\sin(x)) \tag{6}$$

Thus the Lagrange form of the system is given by:

$$L=\frac{1}{2}M\dot{x}^2(1+\cos^2(x))+\frac{1}{2}m((\dot{x}+l\dot{\theta}\cos(\theta))^2+(\dot{x}\cos(x)-l\dot{\theta}\sin(\theta))^2)-Mg\sin(x)-mg(l\cos(\theta)+\sin(x)) \tag{7}$$

Differentiating the Lagrange by θ and x yields (8-9) as given:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right)-\frac{\partial L}{\partial \theta}=\tau \tag{8}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right)-\frac{\partial L}{\partial x}=0 \tag{9}$$

Then by simplicity:

$$\begin{aligned}\tau&=\ddot{x}ml\left(\cos(\theta)-\cos(x)\sin(\theta)\right)+\ddot{\theta}\left(ml^2\right)+\dot{x}^2\left(ml\sin(\theta)\right)+mgl\sin(\theta)\\ 0&=\ddot{x}(M+m)\left(1+\cos^2(x)\right)+\ddot{\theta}ml\left(\cos(\theta)-\cos(x)\sin(\theta)\right)-\dot{x}^2(M+m)\left(\sin(x)\cos(x)\right)-(M+m)g\cos(x)\end{aligned} \tag{10}$$

The state variables are defined as $\mathbb{Z}=[x,\theta]$. Then the derived Lagrange equations can be formed in a following matrix:

$$M(\mathbb{Z})\ddot{\mathbb{Z}}+V(\mathbb{Z},\dot{\mathbb{Z}})\dot{\mathbb{Z}}+G(\mathbb{Z})=U \tag{11}$$

Where:

$$M=\begin{bmatrix} ml\left(\cos(\theta)-\cos(x)\sin(\theta)\right) & ml^2\\ (M+m)\left(1+\cos^2(x)\right) & ml\left(\cos(\theta)-\cos(x)\sin(\theta)\right)\end{bmatrix}$$

$$V=\begin{bmatrix} \left(ml\sin(x)\sin(\theta)\right)\dot{x} & 0\\ -(M+m)\left(\sin(x)\cos(x)\right)\dot{x} & -ml(\sin(\theta)+\cos(\theta))\cos(x)\dot{\theta}\end{bmatrix}$$

$$G=\begin{bmatrix} mgl\sin(\theta)\\ -(M+m)g\cos(x)\end{bmatrix}$$

$$U=\begin{bmatrix}\tau\\0\end{bmatrix}$$

Thus, we can reformulate the Lagrange equation into a 4th order system of ordinary differential equation, then the system dynamic equation appears as following:

$$\dot{\mathbb{Z}}=\begin{bmatrix}0 & 1\\ 0 & M^{-1}V\end{bmatrix}\mathbb{Z}+\begin{bmatrix}0\\ -M^{-1}G\end{bmatrix}+\begin{bmatrix}0\\ -M^{-1}U\end{bmatrix} \tag{12}$$

III. Control System

The Fuzzy-PID control technique can tune the gains of PID controller in real time [11]. In this paper, one a traditional PID controller is designed to compare with proposed controller.

A. Tuning PID Controller

Proportional-integral-derivative (PID) controllers are simple in implementation and have robust behavior [12]. PID controller could be represent as follows:

$$u(t)=K_p\left[e(t)+\frac{1}{T_i}\int_0^t e(\tau)d\tau+T_d\dot{e}(t)\right] \tag{13}$$

Where $T_i=K_p/K_i$ and $T_d=K_d/K_p$ are integral and derivative time constant, respectively. Here, Ziegler-Nichols method is used to adjust the PID gains as well. Based on Ziegler-Nichols technique, the gains are defined zero and also the proportional gain increase up to system reach stable and consistent oscillates, that gain is the ultimate gain K_u [13]. Ultimate gain K_u and the oscillation period T_u used to tune the PID parameters in accordance with Table 1.

Table. 1

Control Type	K_p	T_i	T_d
P	$0,5K_u$	-	-
PI	$0,45K_u$	$T_u/1,2$	-
PD	$0,8K_u$	-	$T_u/8$
PID	$0,6K_u$	$T_u/2$	$T_u/8$

B. Fuzzy- PID Based Control

In Fuzzy-PID control method, the online fuzzy reasoning method is used to turns PID parameters [14]. In fact, the Fuzzy-PID control is consisted of conventional PID and fuzzy logic system, in which the conventional PID controller is used to guarantee the stability of the model. In addition, the fuzzy system can adjust the PID gains online according to the variation of inputs. For tuning the PID controller using fuzzy system according of Fig. 2, the closed loop feedback error of trunk angle e and derivative error $\dot{e}$ are given as inputs of the fuzzy logic control and the outputs are taken as the PID gains K_p, K_d, α that α is defined by:

$$\alpha = K_p^2 / K_i K_d \tag{14}$$

The outputs gains are scaled down between zero and one as follows:

$$K_p' = \left(K_p - K_{p\min}\right) / \left(K_{p\max} - K_{p\min}\right) \tag{15}$$

$$K_d' = \left(K_d - K_{d\min}\right) / \left(K_{d\max} - K_{d\min}\right)$$

The appropriate ranges of the variables are reached as following [15]:

$$K_{p\min} = 0.32K_u, \quad K_{p\max} = 0.06K_u \tag{16}$$

$$K_{d\min} = 0.08K_uT_u, \quad K_{d\max} = 0.15K_uT_u$$

A Fuzzy logic system is knowledge based that is formed from fuzzy If-Then rules. These rules investigate tuning of the PID parameters. Extracting the If-Then rules can be main step in development of the fuzzy controller. Here, due to desired input zero for trunk angle in process, we drive the fuzzy rules that is defined based on the typical zero response of the system. Furthermore, Fuzzy-PID parameter adjusting rules are given following:

(1) When $|e|$ is large, in order to amplify tracking performance, K_p' should be big, and K_d' should be small. In addition, integral gain should be large and α should be set small to reduce of the overshoot and settling time of system.

(2) When $|e|$ and $|\dot{e}|$ are average, K_p' should be small to avoid the biped system have a large overshoot, and in order to stable the system K_d' should be large. In order to avoid the big overshoot and steady state error, the appropriate value of integral gain can be used. In addition, we take medium small for α in this case.

(3) When $|e|$ is small, the better control performance is ensured by K_d' set large .In this case, α depends on derivative error. If derivative error is large, α is large and if derivative error is small, α is small too. Also, the small K_p' results to have not small overshoots in system.

Taking into account the above regulation principles of PID controller, three sets of rules for Fuzzy-PID parameters determine that each set consists of 49 rules as shown in Table 2-4. In this case, we define seven fuzzy sets for K_p' and K_d', and four fuzzy set for α to cover the whole domains of error and derivative error. The membership functions of angle error and derivative error are: (1) Positive Big (PB), (2) Positive Medium (PM), (3) Positive Small (PS), (4) Zero (ZO), (5) Negative Small (NS), (6) Negative Medium (NM), (7) Negative Big (NB) as shown in Fig. 3. In addition, for the membership functions of α we have: (1) Big (B), (2) Medium (M), (3) Medium Small (MS), and (4) Small (S) that is shown in Fig. 4. For K_p', K_d' Big and Small, fuzzy sets are considered according of Fig. 5. The fuzzy rules is consisted product as inference engine, singleton as fuzzifier, and center average as defuzzifie. At the end, the values of K_p', K_d' and α are tuned online.

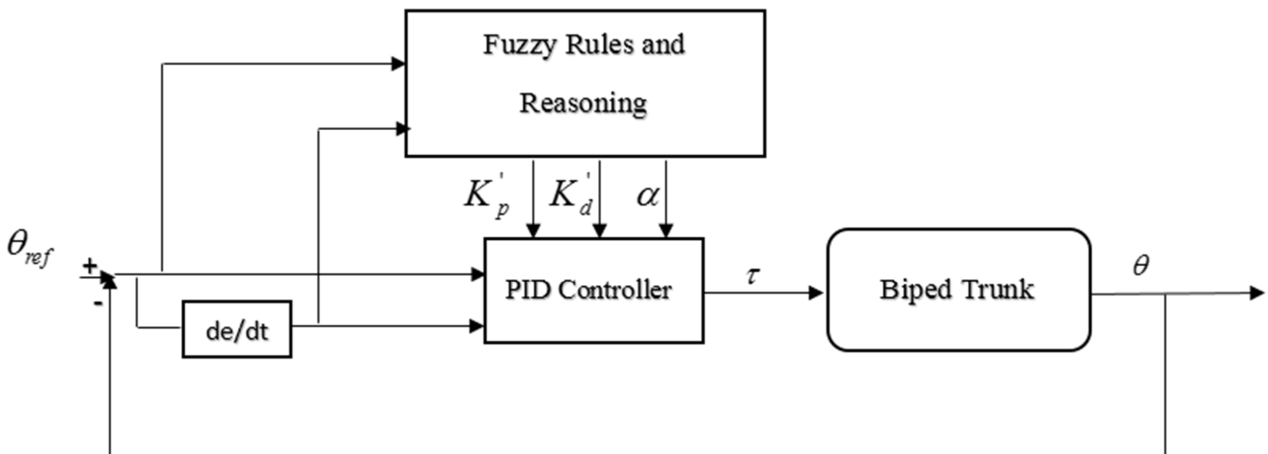

Fig. 2. Fuzzy-PID control system on biped trunk

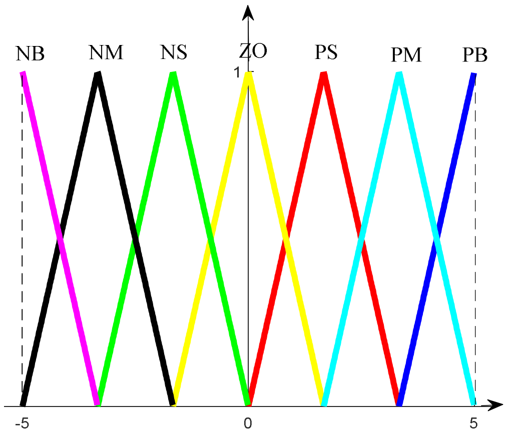

Fig. 3. Memberships functions of $e, \dot{e}$

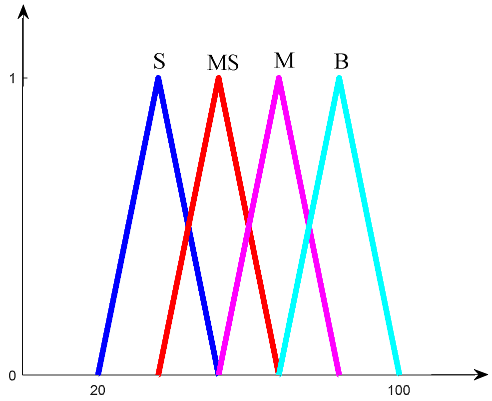

Fig. 4. Memberships functions of α

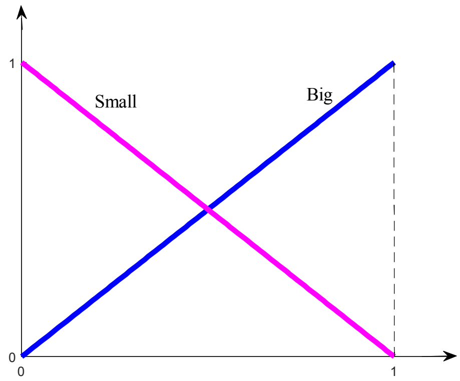

Fig. 5. Memberships functions of $K_p^{'}, K_d^{'}$

Table 2. Fuzzy regulation rules for $K_p^{'}$

		$\dot{e}$						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	B	B	B	B	B	B	B
	NM	S	S	B	B	B	S	S
	NS	S	S	B	B	B	S	S
	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	S	B	B	B	S	S
	PB	B	B	B	B	B	B	B

Table 3. Fuzzy regulation rules for $K_d^{'}$

		$\dot{e}$						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	S
	NS	B	B	B	S	B	B	B
	ZO	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

Table 4. Fuzzy regulation rules for α

		$\dot{e}$						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	S	S	S	S	S	S	S
	NM	MS	MS	S	S	S	MS	MS
	NS	M	MS	MS	S	MS	MS	M
	ZO	B	M	MS	MS	MS	M	B
	PS	M	MS	MS	S	MS	MS	M
	PM	MS	MS	S	S	S	MS	MS
	PB	S	S	S	S	S	S	S

IV. Simulation Results and Discussion

In this section, results of applying the proposed control scheme to biped trunk is presented. A summary of the parameters value of the inverted pendulum is given in Table 5.

Table 5. The parameters value of inverted pendulum

Parameter	Value	Unit
Mass of Trunk COM (m)	0.5	(kg)
Mass of Hip (M)	2	(kg)
Connection Length	1	(m)

The initial conditions of the state variables are $v_0 = 1m/s, \theta_0 = 30\deg$. In addition, the ultimate gain and periods are $k_u = -100, T_u = 1.2$. The PID gains obtained by Ziegler-Nichols method are $k_p = -60, k_d = -400, k_i = -36$. In Fig. 6, the response of biped trunk angle obtained by the Fuzzy-PID and PID controllers is presented. Based on the figure, the Fuzzy control strategy have not any overshoot and undershoot and has steady behavior in the response of zero reference input, while the PID controller has not only steady state error but also some overshoot in the process. In addition to, the performance of these controllers is compared to step desired input. It is illustrated clearly in Fig.7 that the PID-fuzzy controllers is balanced the unstable system as well. However, it can be inferred that the PID controller in comparison of Fuzzy-PID strategy has great overshoot at abrupt changing of input around 70-80 degree that is caused the human body falls or walks inharmonic. In fact, the Fuzzy-PID control gains in accordance of input abrupt changing update online that is results accurate tracking of the reference input for the trunk angle.

The robustness of control strategy applied on trunk balance of human body is more essential in walking process. Therefore, the simulation of proposed control algorithm is considered in the presence of disturbance to validate the robustness of Fuzzy-PID strategy. The disturbance is employed by pulse noise with magnitude of 100 degrees in first and fifth seconds. According of Fig 8-9, the Fuzzy-PID controller provides a more robust system against the external disturbances and human body walks appropriately. Due to poor performance and unstable response of the PID controller on reference changes under abrupt disturbance, the human body severely is the boundary of instability. In this situation, the fuzzy strategy by consideration of adaptive gains is aimed to balance the human body in walking process.

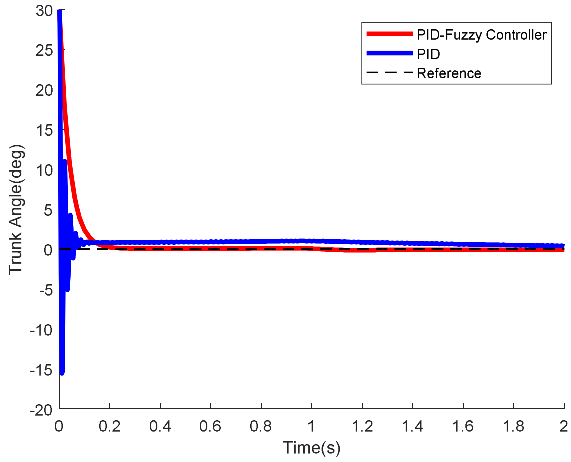

Fig. 6. The response of biped trunk angle to zero desire input, PID and Fuzzy-PID in Confrontation

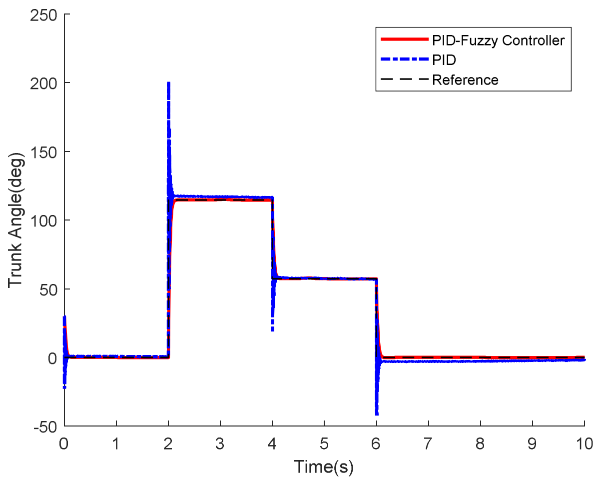

Fig. 7. The response of biped trunk angle to step desire input, PID and Fuzzy-PID in Confrontation

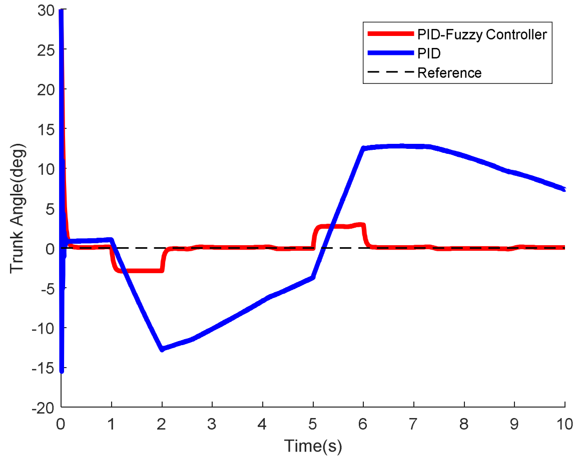

Fig. 8. The response of biped trunk angle to zero desire input under disturbance, PID and Fuzzy-PID in Confrontation

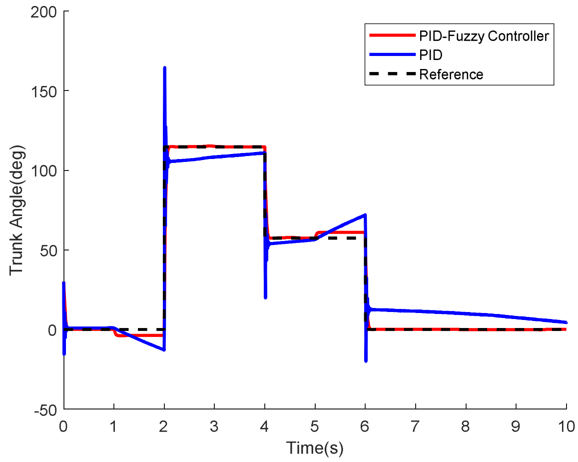

Fig. 9. The response of biped trunk angle to step desire input under disturbance, PID and Fuzzy-PID in Confrontation

V. Conclusion

In this paper, biped trunk in the presence of hip motion disturbances caused by hip displacement of biped is modeled by an inverted pendulum model that travels along a sinusoidal path. The nonlinear dynamic is derived by Lagrange method. In control system, a Fuzzy-PID approach is presented to stabilize the center of mass biped trunk. The fuzzy logic system with tuning gains of PID Controller is employed to stabilize the oscillation angle of the trunk in real time. The performance of the Fuzzy-PID controller is compared with PID Controller tuned on Ziegler-Nichols method. Finally, the robustness of the proposed strategy is verified by imposing disturbance on the hip.

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