Swing Up and Balance Control of Planetary Train Type Pendulum with Fuzzy Logic and Energy Compensation

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Abstract

A planetary train type pendulum is considered in this paper, swing up and balance control is of concern. Due to that the sun gear is not directly connected to the planetary gear, an accelerated-speed profile is required to provide necessary driving torque. In this paper, a fuzzy logic control scheme is considered. Particularly, an energy compensation scenario is proposed so that stabilizing equilibrium can be preserved regardless of the initial positions. Compared with conventional energy-based method, the proposed fuzzy controller provides better control performance with short transition period and disturbance-free.

Keywords: planetary train type pendulum, swing-up, fuzzy control, energy-compensated control.

1. Introduction

Inverted pendulum has been well considered as a benchmark in academic research due to the nonlinear nature. The so-called swing-up and balance control are primary task-oriented concerns. It is interested to drive the pendulum from pending position to steadily upright. In the literature, different types of pendulums can be found such as single pendulum [1], [2], double-link pendulum [4], [6], and pendulum on a car [3-9]. Åström and Furuta proposed an energy-based swinging up controller for an inverted pendulum [1]. It was shown that the globally behavior is characterized by the ratio of the maximum acceleration of the pivot to the acceleration of gravity. In [3], [4], a fuzzy controller based on single input rule modules (SIRMs) was presented, in which each input term is assigned with a SIRM and a dynamic importance degree. A fuzzy swing up control combined with a LQR stabilizing was proposed, where the influence of disturbance was discussed with an adaptive state controller [5]. In recent years, hybrid-control, an integration of unique methods, has been attracted a lot of attention. Lin and Mon proposed a hierarchical fuzzy sliding controller to achieve decoupling performance [6]. Lam etc. investigated the stability with TSK fuzzy logic associated with feedback gains tuned by genetic algorithm [7]. An observer-based hybrid adaptive fuzzy neural network controller combined with a supervisory controller was presented in [8].

In this paper, based on a fuzzy logic, the swing up and balance control of a planetary train type pendulum (PTTP) is addressed. The PTTP has its unique mechanism such that the driving toque for the movement of planetary gear requires accelerated-movement of sun gear. However, while switching to the balance domain, the accumulated energy is possible too high to make the pendulum balanced upright. Therefore, this paper presents an energy compensation scenario so that the swing up and balance of PTTP can be achieved. Compared to conventional method, energy-based swing up and LQR balance [9-11], the proposed fuzzy control scheme indeed provides better control performance in the sense of simplicity and robustness. In fact, the stabilization of PTTP is achieved by the proposed energy-compensated fuzzy controller regardless of starting positions and disturbances.

This paper is organized as follows. Section 2 presents the system model formulation that comprises the models of PTTP and DC motor. The energy-based swing up control and the LQR balance control are described in Section 3. The proposed approach, involving swing up control, balance control, and energy compensation, is addressed in Section 4. In Section 5, simulation results, compared to conventional control methods, are provided.

2. System Model of Planetary Train Type Pendulum

The configuration of PTTP is shown in Figure 1, where m_1 denotes the planetary gear, o_1 is the pivot of the planetary gear, m_2 denotes the sun gear, o_2 is the pivot of the sun gear, and m_0 denotes the pendulum pole. The pendulum pole and the planetary gear rotate around the sun gear, while the sun gear is static. When the pendulum pole is fixed, each of the sun gear and planetary gear can revolve with the same angular speed but opposite direction. To obtain the mathematical model of PTTP, the associated Euler-Lagrange dynamic equation needs to be addressed. The system symbols are showed in Table 1.

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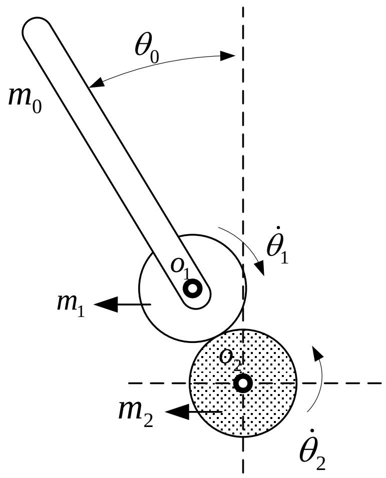


Figure 1. Scheme diagram of PTTP.

Table 1. System parameters

θ_0	pendulum angle	
θ_2	motor angle	
m_0	pendulum mass	0.027 *kg*
m_1	Planet gear mass	0.035 *kg*
m_2	sun gear mass	0.038 *kg*
m_3	payload mass	0.02 *kg*
m_4	gear stand mass	0.95 *kg*
L_0	pendulum length	0.11 *m*
L_4	gear stand length	0.05 *m*
L_3	payload length	0.02 *m*
g	gravity acceleration	9.8 m/s^2
r_1	radius of planet gear	0.013 *m*
r_2	radius of sun gear	0.13 *m*
J_0	pendulum inertia	1.543×10^{-3} $kg\text{-}m^2$
J_1	planet gear inertia	0.958×10^{-6} $kg\text{-}m^2$
J_2	sun gear inertia	3.211×10^{-6} $kg\text{-}m^2$

A. *Model of PTTP*

A typical Euler-Lagrange dynamic equation is presented as follows：

$$\frac{d}{dt}\left[\frac{\partial L}{\partial \dot{q}}\right]-\frac{\partial L}{\partial q}=Q \tag{1}$$

$$q=\begin{bmatrix}\theta_0\\ \theta_2\end{bmatrix}\quad Q=\begin{bmatrix}\tau_0\\ \tau_2\end{bmatrix} \tag{2}$$

where $L=K-P,K$ is the kinetic energy, P is the potential energy, τ_2 is the torque of sun gear provided by a DC motor, and τ_0 is the exogenous torque to pendulum. It is noted that τ_0 is physically considered as the disturbance to the pendulum pole.

PTTP basically looks like other motor-driven pendulums at glance. However, the PTTP has its unique mechanism that the coupling between sun gear and planetary gear is not directly connected. It means that the movement of planetary gear requires an accelerated-speed driving profile from sun gear. Otherwise, a constant-speed sun gear will make no effort and the planetary gear will remain at its static position. Likewise, the coupling between planetary gear and pendulum pole is not directly coupled neither. The sun gear is mounted on a DC motor which provides the necessary torque of interest. Possible interactions among sun gear, planetary gear, and pendulum pole are investigated as follows：

- Pendulum pole is static ($\dot{\theta}_0=0$):

  The relation between sun gear and planetary gear is formulated as

$$\frac{\dot{\theta}_1'}{\dot{\theta}_2}=-\frac{N_1}{N_2}=-\frac{r_2}{r_1} \tag{3}$$

- Sun gear is static ($\dot{\theta}_2=0$):

  The tangent velocity, v, and the angular velocity of the planetary gear are show as (4) and (5), respectively.

$$v=(r_1+r_2)\dot{\theta}_0 \tag{4}$$

$$\dot{\theta}_1''=\frac{v}{r}=\frac{r_1+r_2}{r_1}\dot{\theta}_0 \tag{5}$$

where $\dot{\theta}_1'$ and $\dot{\theta}_1''$ are denoted as the planetary gear velocity when $\dot{\theta}_0=0$ and $\dot{\theta}_2=0$, respectively. From (3) and (5), the angular speed of planetary gear associated with the situations of sun gear and pendulum pole can be obtained as

$$\dot{\theta}_1=\dot{\theta}_1'+\dot{\theta}_1''=-\frac{r_2}{r_1}\dot{\theta}_2+\frac{r_1+r_2}{r_1}\dot{\theta}_0 \tag{6}$$

The kinetic energy of pendulum pole is

$$K_0=\frac{1}{2}J_0\dot{\theta}_0^{\,2} \tag{7}$$

Based on the structure of PTTP, the integrated inertia, including gear stand, pendulum, and payload, is obtained as follows

$$\begin{aligned}J_0&=J_{04}+J_{00}+J_{03}\\&=\frac{m_4}{3}L_4^{\,2}+\frac{m_0}{3L_0}\left[(L_0+L_4)^3-L_4^{\,3}\right]\\&\quad+\frac{m_3}{3L_3}\left[(L_0+L_4)^3-(L_4+L_0-L_3)^3\right]\end{aligned} \tag{8}$$

Similarly, the potential energy of PTTP can be derived as follow:

$$\begin{aligned}P_0&=P_{04}+P_{00}+P_{03}\\&=\left[m_4\frac{L_4}{2}+m_0\left(\frac{L_0}{2}+L_4\right)\right.\\&\quad\left.+m_3\left(L_0+L_4-\frac{L_3}{2}\right)\right]\cdot g\cos\theta_0\end{aligned} \tag{9}$$

The kinetic energy and potential energy of the planetary gear is represented as (10) and (11), respectively.

$$K_1 = \frac{1}{2}m_1 v^2 + \frac{1}{2}J_1\dot{\theta}_1^2$$
$$= \frac{1}{2}m_1(r_1+r_2)^2\dot{\theta}_0^2 + \frac{1}{2}J_1\left(\frac{r_2}{r_1}\right)^2\dot{\theta}_2^2 \tag{10}$$
$$+\frac{1}{2}J_1\left(\frac{r_1+r_2}{r_1}\right)^2\dot{\theta}_0^2 - J_1\frac{r_2(r_1+r_2)}{r_1^2}\dot{\theta}_0\dot{\theta}_2$$

$$P_1 = m_1 g(r_1+r_2)\cos\theta_0 \tag{11}$$

The kinetic energy and the potential energy of the sun gear are described as follow

$$K_2 = \frac{1}{2}J_2\dot{\theta}_2^2 \tag{12}$$

$$P_2 = 0 \tag{13}$$

From (1) and (8)-(13), the Euler-Lagrange dynamic equation can be derived as follows:

$$\frac{d}{dt}\left[\frac{\partial L}{\partial\dot{\theta}_0}\right] - \frac{\partial L}{\partial\theta_0}$$
$$= \left[J_0 + J_1\left(\frac{r_1+r_2}{r_1}\right)^2 + m_1(r_1+r_2)^2\right]\ddot{\theta}_0 - J_1\frac{r_2(r_1+r_2)}{r_1^2}\ddot{\theta}_2 \tag{14}$$
$$-\left[m_0\left(\frac{L_0}{2}+L_4\right) + m_1(r_1+r_2) + m_3\left(L_0+L_4-\frac{L_3}{2}\right)\right.$$
$$\left.+m_4\frac{L_4}{2}\right]\cdot g\sin\theta_0 = \tau_0$$

$$\frac{d}{dt}\left[\frac{\partial L}{\partial\dot{\theta}_2}\right] - \frac{\partial L}{\partial\theta_2} = -J_1\frac{r_2(r_1+r_2)}{r_1^2}\ddot{\theta}_0 + \left[J_1\left(\frac{r_2}{r_1}\right)^2 + J_2\right]\ddot{\theta}_2 = \tau_2 \tag{15}$$

B. *Model of DC Motor*

The DC motor, directly connected with the sun gear, is used to provide necessary torque as require. The electrical equation of a DC motor is represented as follows

$$E_a = L_a\dot{I}_a + R_a I_a + K_b\dot{\theta}_2 \tag{16}$$

where I_a, R_a, and L_a are the current, resistance, and inductance of armature, respectively. Since the value of inductance is small enough, $L_a = 0.26\cdot 10^{-3}$ (H), the term $L_a\dot{I}_a$ can be ignored for simplicity. Thus, the torque τ_2 for the sun gear can be obtained

$$\tau_2 = K_t I_a = -\frac{K_t K_b}{R_a}\dot{\theta}_2 + \frac{K_t}{R_a}E_a \tag{17}$$

In the case that the exogenous torque is zero, $\tau_0 = 0$, substituting (17) into (14) and (15), it leads to the mathematical model of PTTP as (18).

3. Conventional Control

In this section, the energy-based swing up control and LQR balance control will be briefly illustrated.

A. *Swing Up Control*

Swinging up the pendulum often adopts the energy-based control approach that is easy to be implemented. Basically, how to accumulate the system energy is the main issue of concern [1, 9-11]. Let E be the system energy, the sum of kinetic energy and potential energy. Without loss of generality, E is set to be zero at stable equilibrium point, $\theta_0 = 0^\circ, \dot{\theta}_0 = 0$. In the standstill situation, $\theta_2 = 0^\circ$, $\dot{\theta}_2 = 0$, system energy can be expressed as

$$E = \left[\frac{1}{2}J_0 + \frac{1}{2}J_1\left(\frac{r_1+r_2}{r_1}\right)^2 + \frac{1}{2}m_1(r_1+r_2)^2\right]\dot{\theta}_0^2$$
$$+\left[m_0\left(\frac{L_0}{2}+L_4\right) + m_1(r_1+r_2)\right. \tag{19}$$
$$\left.+m_3\left(L_0+L_4-\frac{L_3}{2}\right) + m_4\frac{L_4}{2}\right]g(\cos\theta_0 - 1)$$

From (18)-(20), the control law according to [1] is

$$\ddot{\theta}_2 = k_r sign(\dot{\theta}_0) \tag{20}$$

where k_r is a positive constant. The derivative of E by applying $u_r = \ddot{\theta}_2$ can be obtained as

$$\frac{dE}{dt} = J_1\frac{r_2(r_1+r_2)}{r_1^2}\dot{\theta}_0\cdot u_r \tag{21}$$

Equivalently, it gives that

$$\frac{dE}{dt} = J_1\frac{r_2(r_1+r_2)}{r_1^2}\cdot k_r\cdot\left|\dot{\theta}_0\right| \ge 0 \tag{22}$$

From (22), it can be seen that the rate of energy increasing is proportional to the value of k_r, i.e. the upswing period is shorter with a larger k_r.

B. *Balance Control*

Traditional methods employ state-feedback control to stabilize, where pole placement and LQR are typical ones to be considered [9]. LQR control is a cost-oriented optimal control method, where with certain weighting matrices a quadratic form cost (23) is minimized and the optimal state feedback gains k_c can be derived (24). In this case, the state variables are θ_0, θ_2, $\dot{\theta}_0$, and $\dot{\theta}_2$.

$$J = \int_0^\infty\left[x^T(t)Qx(t) + u^T(t)Ru(t)\right]dt \tag{23}$$

$$u(t) = -k_c x(t) \tag{24}$$

where $x(t)$ is the state vector, $u(t)$ is the control variable, $Q \ge 0$ and $R > 0$.

It is obviously that to apply LQR control to the balance control of PTTP, certain linearization around the unstable equilibrium point is required. However, it will result in the conservation of stabilization.

$$\begin{bmatrix} J_0 + J_1\left(\frac{r_1+r_2}{r_1}\right)^2 + m_1(r_1+r_2)^2 & -J_1\frac{r_2(r_1+r_2)}{r_1^{\,2}} \\ -J_1\frac{r_2(r_1+r_2)}{r_1^{\,2}} & J_1\left(\frac{r_2}{r_1}\right)^2 + J_2 \end{bmatrix}\begin{bmatrix}\ddot{\theta}_0 \\ \ddot{\theta}_2\end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \frac{K_t K_b}{R_a}\end{bmatrix}\begin{bmatrix}\dot{\theta}_0 \\ \dot{\theta}_2\end{bmatrix}$$
$$+\begin{bmatrix} -\left[m_0\left(\frac{L_0}{2}+L_4\right)+m_1(r_1+r_2)+m_3\left(L_0+L_4-\frac{L_3}{2}\right)+m_4\frac{L_4}{2}\right]\cdot g\sin\theta_0 \\ 0\end{bmatrix} = \begin{bmatrix} 0 \\ \frac{K_t}{R_a}\end{bmatrix}E_a \qquad (18)$$

4. Fuzzy Controller Design

The proposed fuzzy controller integrates with three unique parts: swing up control, balance control, and energy compensation.

A. *Fuzzy Swing Up Control*

A scheme diagram, shown in Figure 2, is helpful to describe the concept of proposed work. The pendulum positions at stable and unstable equilibrium points are 0 and π (rad), respectively. In Figure 2, the shaded and dashed regions describe the swing up and stabilization zones, respectively. The region of balance domain is chosen as $\theta_0 \in [-\pi/12, \pi/12]$, which is used to decide when the swing up control will switch to the balance control. Also, the signs of direction-related parameters, $\dot{\theta}_0$ and *u*, are defined that negative (positive) sign means counterclockwise (clockwise) direction. In this case, *u* is the armature voltage E_a, which provides required torque τ_2. During the swing up process, to make the pending period shorter, it is nature to apply driving torque as large as possible, i.e. $E_a = +10V$ when pendulum in the left half region, $E_a = -10V$ otherwise. The proposed fuzzy inference system is expressed as

$$R_i : IF\ X = A_{i1}\ and\ Y = A_{i2}\ THEN\ u = B_i \qquad (26)$$

where R_i is the *i*th fuzzy relation, *X* and *Y* are the input variables, *u* is the output variable, A_{i1}, A_{i2} are the fuzzy sets in premise part, and B_i is the fuzzy set in the consequent part. To calculate the output *u*, the centroid method is used for defuzzification.

With fuzzy swing up controller, the input and output membership are show in Figure 3, and the fuzzy inference rules are given as follow.

R_1 : IF θ_0 is PO Then E_a is NB

R_2 : IF θ_0 is NE Then E_a is PB

B. *Fuzzy Balance Control*

the balance control, θ_0 and $\dot{\theta}_0$ are considered as inputs, and the armature voltage E_a is the output. In Figure 2, while $|\theta_0| \le \pi/12$ (rad), it will automatically switch to the balance control strategy. Based on experience and understanding of system characteristics, membership functions of the premise and consequent parts are defined in Figure 4. Equivalently, when θ_0 and $\dot{\theta}_0$ are NB (PB), the voltage E_a need to be exerted such as PB (NB), so that the pendulum will rotate clockwisely (counterclockwisely) to the upright position, then θ_0 and $\dot{\theta}_0$ will converge toward Z. The fuzzy inference rules are summarized as Table 2.

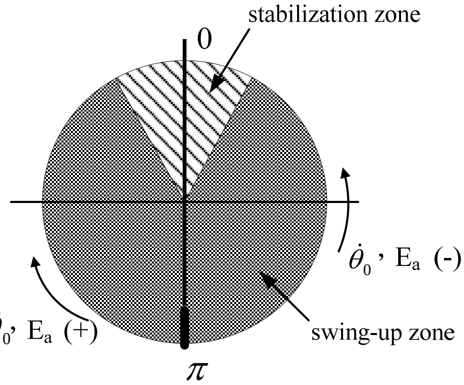
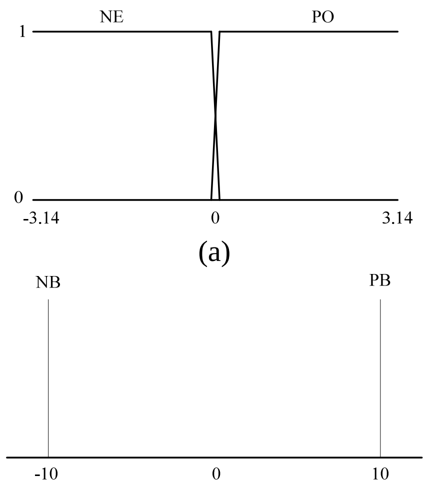


Figure 2. Scheme diagram of swing up



(b)

Figure 3. Membership functions of fuzzy swing up controller: (a) θ_0, (b) E_a.

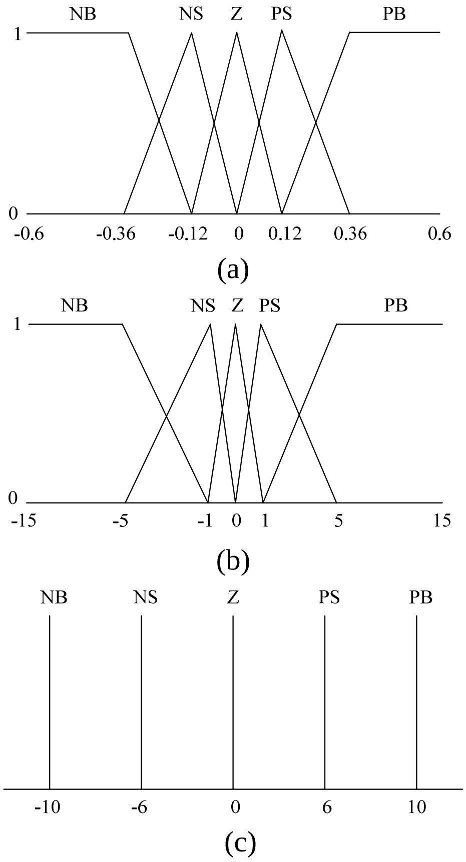


Figure 4. Membership functions of fuzzy balance controller: (a) θ_0, (b) $\dot{\theta}_0$, (c) E_a.

Table 2. Fuzzy Rules

θ_0 \ $\dot{\theta}_0$	NB	NS	Z	PS	PB
NB	PB	PB	PB	PS	Z
NS	PB	PB	PS	Z	NS
Z	PB	PS	Z	NS	NB
PS	PS	Z	NS	NB	NB
PB	Z	NS	NB	NB	NB

C. *Energy Compensation Controller*

In practice, the choice of starting position needs more consideration. In fact, if the angle between the pendulum and the stable equilibrium point is larger, the upswing accumulated energy will be larger as well. Consequently, it is more difficult to precede next stabilization in the balance region. Also it is interest to investigate the stability robustness, the effect caused from sudden disturbance. This paper mainly presents an energy compensated fuzzy controller for PTTP to improve the robust stability regardless initial positions, and the system block diagram is shown in Figure 5.

The potential energy and dynamic energy of pendulum can be represented in the following.

$$P = \left[m_4 \frac{L_4}{2} + m_0 \left(\frac{L_0}{2} + L_4 \right) + m_3 \left(L_0 + L_4 - \frac{L_3}{2} \right) \right] \cdot g \cdot (\cos\theta_0 - 1) \quad (27)$$

$$K = \frac{1}{2} J \dot{\theta}_0^{\,2} \quad (28)$$

According to the system parameters in Table 1, the extreme values of potential and kinematics energy can be calculated as follows

$$P = \begin{cases} -0.566, & \theta_0 = 180^\circ \\ 0, & \theta_0 = 0^\circ \end{cases} \quad (29)$$

$$K = \begin{cases} 0.566, & \theta_0 = 180^\circ \\ 0, & \theta_0 = 0^\circ \end{cases} \quad (30)$$

Hence, the maximum total energy at unstable equilibrium position, $\theta_0 = 0^\circ$, equals to 0. It means that if the total energy is larger than 0, the pendulum can not be stabilized upright, regardless any effort from driving torque. In this paper, the input variables of the energy compensator are system energy E and $\dot{\theta}_0$, and the output is the compensating voltage. The associated membership functions are shown in Figure 6.

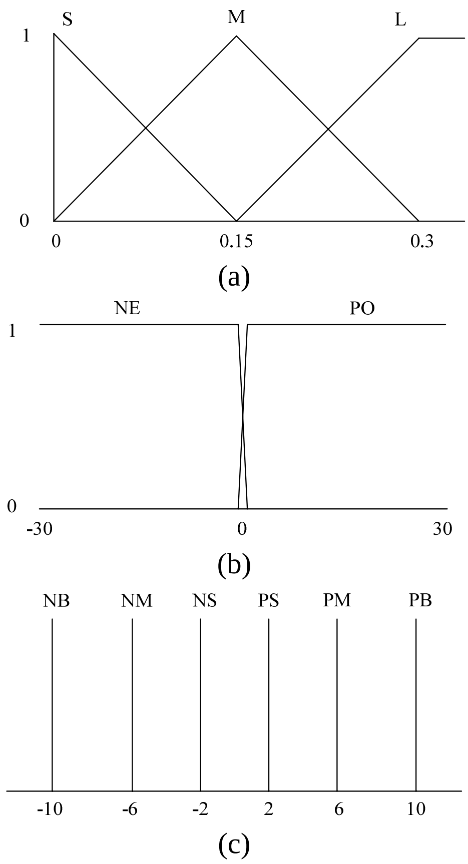


Figure 6. Membership functions of fuzzy energy compensated controller: (a) E, (b) $\dot{\theta}_0$, (c) E_a.

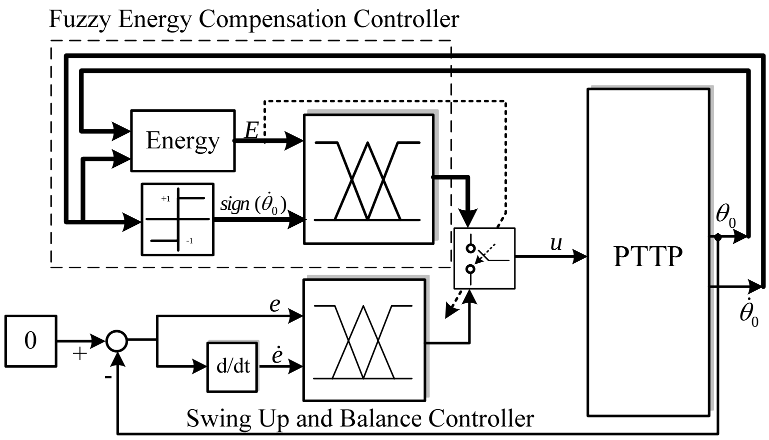


Figure 5. System configuration of proposed energy-compensated swing and balance control.

The design concept is explained in the following:

- E is S and $\dot{\theta}_0$ is PO (NE): Since E is slightly larger than 0, it requires a small compensated energy, and if $\dot{\theta}_0$ is PO (NE), then the output compensated voltage is NS (PS).
- E is M and $\dot{\theta}_0$ is PO (NE): Since E is larger than 0, the required compensated energy is larger than that in the previous case, and if $\dot{\theta}_0$ is PO (NE), then the output compensated voltage is NM (PM).
- E is L and $\dot{\theta}_0$ is PO (NE): Since E is significantly larger than 0, it requires a large compensated energy, and if $\dot{\theta}_0$ is PO (NE), then the compensated voltage is NB (PB).

5. Simulation Results

Simulation results regarding the comparison of conventional methods and proposed work are shown in Figures 7-14, where the initial conditions are $\theta_0 = \pi$ (rad) and $\dot{\theta}_0 = 0$ (rad/sec). To highlight the effect of robustness, a certain disturbance is added at $t = 10$ (sec). It can be seen that, from Figures 7-8, with the conventional energy-based method the system energy keeps increasing, $t > 10$, that leads to nonstop rotating. It is also noted that, from Figures 9-10, with fuzzy controller, the pendulum pole can be stabilizing much faster that the energy-based method does. However, without the energy compensation, the stability fails subject to disturbance. The effect of energy compensation can be illustrated in Figures 11-14. In this case, the stability robustness of system energy and pendulum position has been improved significantly. When the extra force is added, the system energy is suddenly raised and the energy-compensation controller is starting to work. It is obviously that, with energy compensation scheme, the extra accumulated energy can be quickly compensated, and the stability can be recovered as well subject to disturbance to the pendulum pole. To further highlight the effect of proposed work, different initial conditions are considered. From Figures 15-16, it illustrates that the pendulum pole can be stabilized upright regardless of the initial position and speeds, and the control performance via proposed energy compensation is much better than the conventional methods.

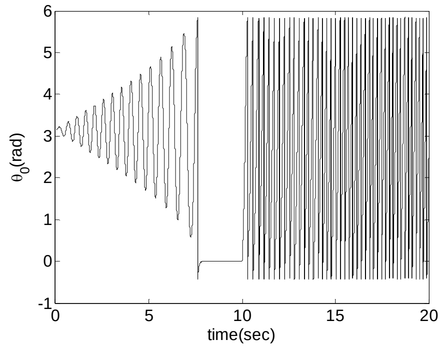


Figure 7. Position response (energy-based swing up and LQR balance control)

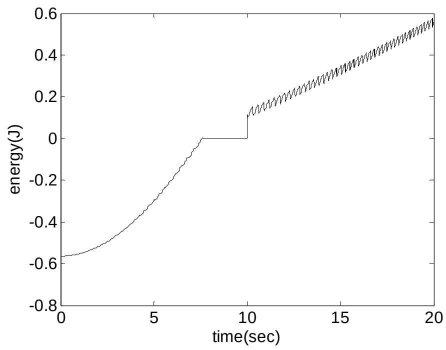


Figure 8. Energy response (energy-based swing up and LQR balance control)

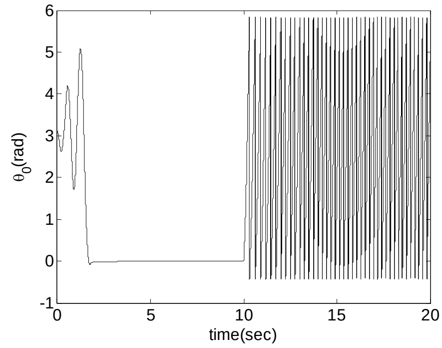


Figure 9. Position response (fuzzy control without energy compensation)

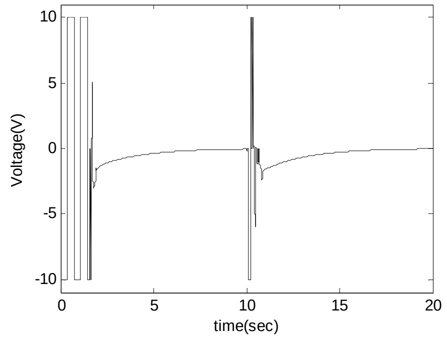


Figure 13. Output of fuzzy swing-up/balance controller (fuzzy control with energy compensation)

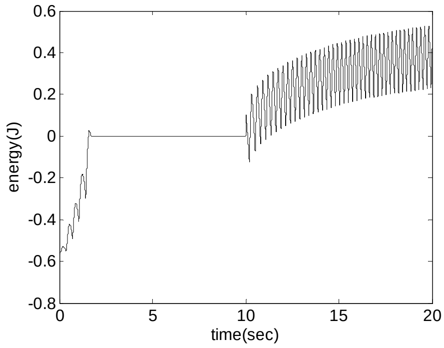


Figure 10. Energy response (fuzzy control without energy compensation)

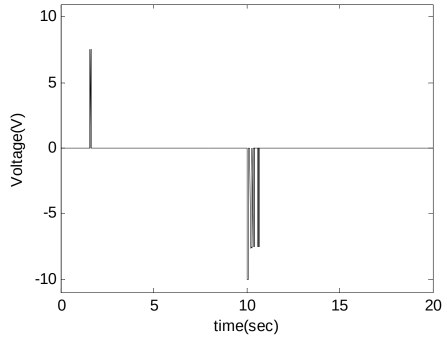


Figure 14. Output of energy-compensation controller (fuzzy control with energy compensation)

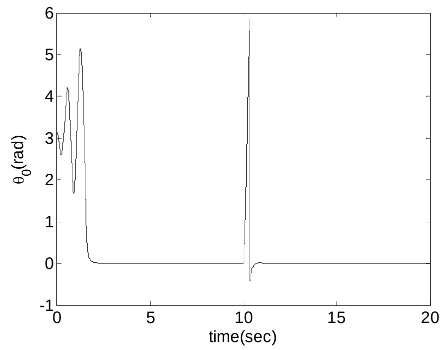


Figure 11. Pendulum pole response (fuzzy control with energy compensation)

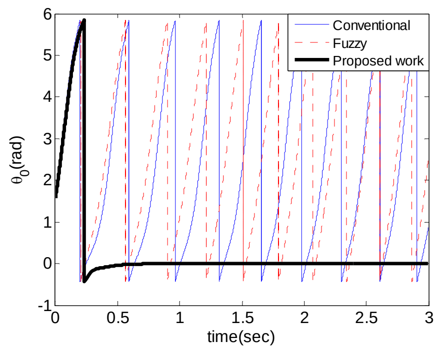


Figure 15. Position response: $\theta_0(0) = 90°, \dot{\theta}_0(0) = 20$

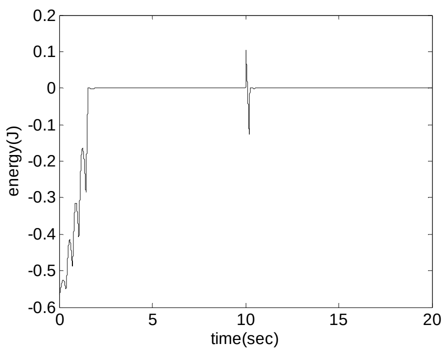


Figure 12. Energy response (fuzzy control with energy compensation)

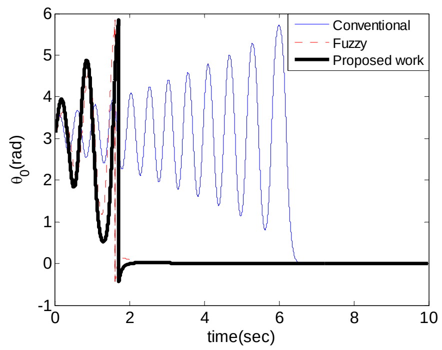


Figure 16. Position response: $\theta_0(0) = 180°, \dot{\theta}_0(0) = 5$

6. Conclusions

This paper proposes a fuzzy controller for the swing up and balance control of a planetary train type pendulum. Due to the unique mechanism of PTTP, the output torque for the required control performance, fast swing-up and stability robustness, needs further consideration. In particular, an energy-compensation scheme is designed so that the extra accumulated energy can be compensated. Compared with conventional energy-based and LQR combined control, simulation results illustrate that the proposed fuzzy control scheme indeed provide better control responses in the viewpoint of disturbance rejection.

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