FUZZY PID CONTROLLER FOR PROPELLER PENDULUM

Yener TASKIN

Department of Mechanical Engineering, Istanbul University, Turkey
ytaskin@istanbul.edu.tr

Abstract: *In this paper, a fuzzy PID controller is proposed for angular position control of a nonlinear propeller pendulum system. While classical control methods work well on linear systems, nonlinear control approaches should be designed for nonlinear ones. On the one hand, there are three constant gains related with linear proportional, integral and derivative terms in classical PID controller. On the other hand, these gains are varied with time by the proposed controller using fuzzy logic inference. In order to demonstrate the position control enhancement for the nonlinear system, the proposed controller is compared with classical PID controller using simulation results with and without external disturbance. The simulation results show that the proposed Fuzzy PID controller is more successful in reference tracking than classical PID controller.*
Keywords: *Fuzzy logic, PID, angular position, nonlinear control, propeller pendulum***.**

1. Introduction

Propeller pendulum is a type of compound propeller which is described as having a motorized propeller producing a thrust force at the end of a pendulum rod that can lift the pendulum up and down [1]. The thrust force can be utilized to stabilize the pendulum at any desired position using various control methods [1-7]. A PID method is preferred to control a driven pendulum in [2]. Kizmaz et al. also proposed a sliding mode controller using the linear part of the mathematical model of suspended pendulum system [3].

Propeller pendulum is assumed to be a simplified plant model of an unmanned autonomous vehicle which is used for teaching system dynamics and control topics in mechanical and mechatronics engineering education [8-11]. Huba et al. utilized a pendulum control to demonstrate different aspects of robust and nonlinear control for “learning by playing”, “learning by discovering”, or through “experiential learning” approaches during engineering education [8].

Propeller pendulum is a nonlinear system and can be controlled well by classical control methods when the system is linearized around design point. But, if the controlled state goes far away from the design point and/or the system is highly nonlinear, at this point, classical control methods such as PID control can hardly hold the dynamic performance [10]. Therefore, nonlinear pendulum system is a significant candidate to develope a nonlinear controller. In literature, various structures for fuzzy PID controllers have been proposed for various applications since fuzzy controllers demonstrate successful results [12-14]. In this paper, a fuzzy PID controller with a new structure is proposed for a nonlinear propeller pendulum system. Primarily, propeller pendulum is presented in the next section. Afterwards, the proposed Fuzzy PID controller is described briefly and then the discussion of simulation results and conlusions are given in the following sections respectively.

2. Propeller Pendulum

Figure 1 exhibits propeller pendulum model with an external disturbance force F_d applied perpendicular to pendulum rod. In this model, m_1 and m_2 represent the mass of pendulum rod and motorized propeller respectively. Desired angular position *theta* is measured during propeller thrust force T is applied. L is the length of propeller pendulum. In equation (1), nonlinear mathematical model of propeller pendulum is given. J and c are the moment of inertia of propeller pendulum and viscous damping coefficient respectively. g is the acceleration of gravity. Model parameters and their values are given in Table 1 [11].

Table 1. Model parameters [11]

Parameter	***SI Units***	***Value***
m_1	kg	0.21
m_2	kg	0.16
L	m	0.6
J	$\mathrm{kg\,m^2}$	0.083
c	$\mathrm{kg\,m^2}/s$	0.074
g	m/s^2	9.81

Received on: 15.08.2016
Accepted on: 19.12.2016

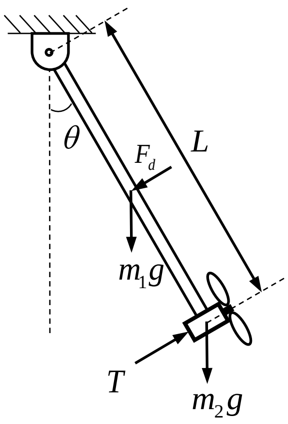


Figure 1. Propeller pendulum model

$$J\ddot{\theta}+c\dot{\theta}+\left(\frac{m_1}{2}+m_2\right)gL\sin\theta=TL-F_d\frac{L}{2} \tag{1}$$

3. Fuzzy PID Controller

In classical PID control, the present, past and future errors are compensated by linear proportional, integral and derivative terms. Thrust force can be obtained by the sum of these terms as seen in equation (2) where K_P, K_I and K_D are constants. Error is defined by difference between desired reference angular position and angular position of pendulum given in equation (3).

$$T_{PID}=K_Pe+K_I\int edt+K_D\frac{de}{dt} \tag{2}$$

$$e=\theta_{ref}-\theta \tag{3}$$

In proposed fuzzy PID control, the gains are not constant anymore. Each controller gain is calculated by a fuzzy logic unit and varied with time. This unit is shown in Figure 2 with a single input - single output relation.

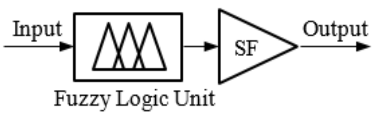


Figure 2. Fuzzy logic input-output representation

Time varied gains of Fuzzy PID are obtained from related fuzzy logic unit. The input is the related variable and the output is the related variable gain of the proposed controller. SF is the related scaling factor. In Table 2, the input-output relations are given for the related terms of proposed fuzzy PID controller. If input of the fuzzy logic unit is chosen as error (e), then scaling factor and output of the unit are taken as proportional scaling factor (PSF) and gain of the proportional controller (K_{FP}). If input of the fuzzy logic unit is chosen as integral of error ($\int edt$), then scaling factor and output are taken as integral scaling factor (ISF) and gain of the integral controller (K_{FI}). If input of the fuzzy logic unit is chosen as derivative of error (de/dt), then scaling factor and output are taken as derivative scaling factor (DSF) and gain of the derivative controller (K_{FD}). Thrust force generated from the proposed fuzzy PID controller is the sum of these terms and is obtained by equation (4).

$$T_{FuzzyPID}=K_{FP}e+K_{FI}\int edt+K_{FD}\frac{de}{dt} \tag{4}$$

The structure of the proposed controller is given in Figure 3. Block diagram shown in Figure 4 exhibits the control thrust force applied to propeller pendulum in the closed loop form.

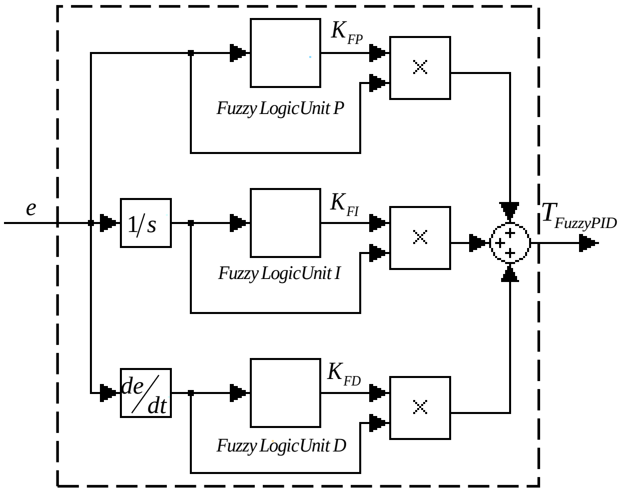


Figure 3. Structure of Fuzzy PID controller

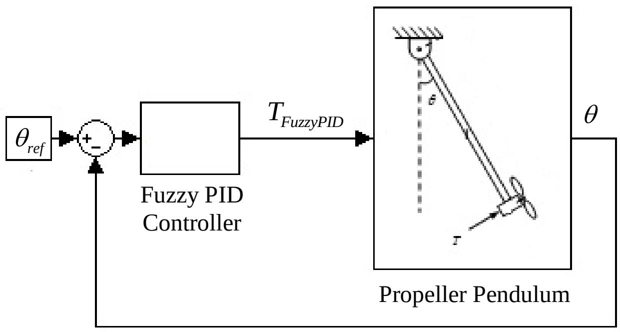
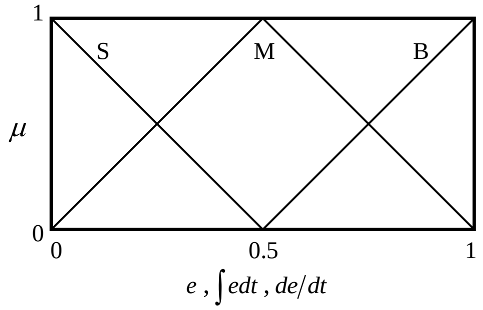


Figure 4. Block diagram of closed loop fuzzy PID controller of propeller pendulum

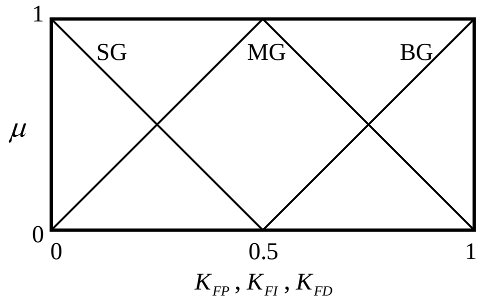
Table 2. Fuzzy logic input-output relation

Input	***Scaling Factor (SF)***	***Output***
e	PSF	K_{FP}
$\int edt$	ISF	K_{FI}
de/dt	DSF	K_{FD}

For each fuzzy logic unit of the proposed controller, Mandani type fuzzy inference with triangular membership functions is utilized and centroid method is used for defuzzification. Membership functions are shown in Figure 5 for input and output variables.



(a)



(b)

Figure 5. Membership functions a) input variables b) output variables

Fuzzy rule base is very simple and given in Table 3. It involves the same rules for each fuzzy logic unit.

Table 3. Rule base of each fuzzy logic unit

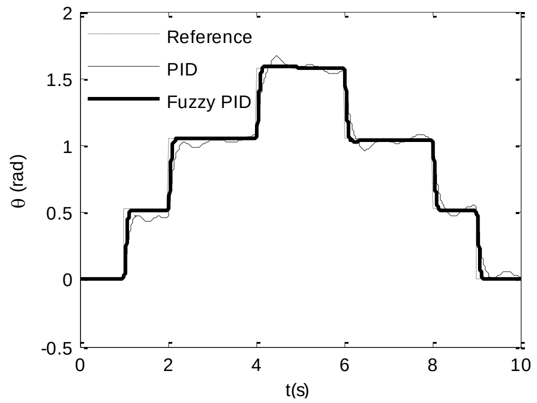
Input			***Output***		
e	$\int edt$	de/dt	K_{FP}	K_{FI}	K_{FD}
S			SG		
M			MG		
B			BG		

- If input is small (S) then output gain is small (SG)
- If input is medium (M) then output gain is medium (MG)
- If input is big (B) then output gain is big (BG)

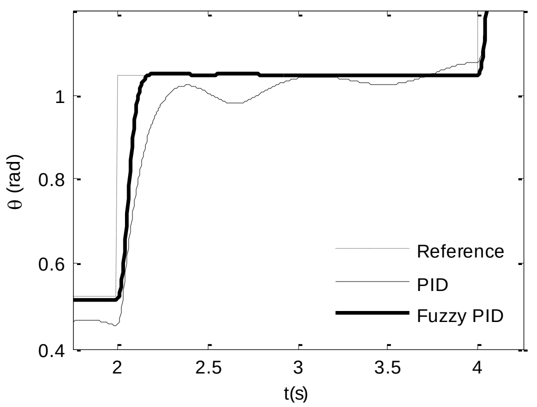
For instance, if angular position error is small, then proportional gain will be small. On the other hand, if the error is big, then the proportional gain will be big. Scaling factors of related terms are tuned by trial and error during simulation. Proportional (PSF), integral (ISF) and derivative (DSF) scaling factors are taken as 250, 100 and 11 respectively. Constant gains of classical PID controller are taken as 150, 50 and 2 for proportional (K_P), integral (K_I) and derivative (K_D) terms respectively. Thrust force is limited to ±20 N for motorized propeller.

4. Simulation Results

Position control of the propeller pendulum is evaluated by simulation results with and without external disturbance cases. Simulation duration and sampling time is taken as 10 and 0.005 seconds, respectively. Equation of motion is solved by Runge-Kutta method. Primarily without external disturbance simulation is made. Position reference is described by ascending and descending steps shown in Figure 6 a. The simulated position of the propeller pendulum is also demonstrated in the same figure for both classical PID and proposed fuzzy PID controllers. Pendulum stays still at the beginning position for one second. Afterwards, the position reference ascends to $\pi/6$ rad, $\pi/3$ rad and $\pi/2$ rad steps respectively. Then, pendulum follows the reference by descending to the beginning position symmetrically. While pendulum follows the reference very close in fuzzy PID controlled case, PID controlled case demonstrates different responses for each step during ascending and descending. PID controller demonstrates weak tracking performance since classical linear control methods do not work well on controlling nonlinear systems. This situation can be seen in Figure 6 b clearly. On the other hand, Fuzzy PID controlled pendulum follows the reference track without overshooting in each ascending and descending steps.



(a)



(b)

Figure 6. Angular position of propeller pendulum a) for 10 s duration b) between 1.75 s and 4.25 s

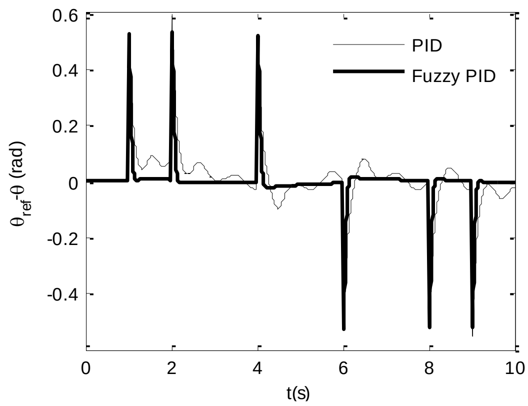


Figure 7. Error of angular position

Reference tracking success of the proposed controller can be evaluated in angular positon error diagram as well as angular position diagram. In Figure 7, it is easy to see that the angular position error of fuzzy PID controller goes to zero rapidly after each step reached up and down. On the other hand, in classical PID case, the position of pendulum can't reach to step value or remains positive or negative position errors in each step.

While the gains are constant in classical PID controller, the gains of fuzzy PID controller are varied with time according to fuzzy inference which is described in the previous section. Variation of each control gain of fuzzy PID is plotted in Figure 8 for reference tracking simulation shown in Figure 6 a. Fuzzy proportional (K_{FP}), integral (K_{FI}) and derivative (K_{FD}) gains are changed as angular position error, integral of angular position error and derivative of angular position error are changed with the nonlinear behavior of the pendulum system. For instance, when the error increases, proposed fuzzy PID controller generates greater proportional gain in order to achieve better tracking performance. On the other hand, when the error goes to zero, it descends to lower values. The variation of the other two gains indicates the same character as the integral of error or the derivative of error increases, the related gains take greater values.

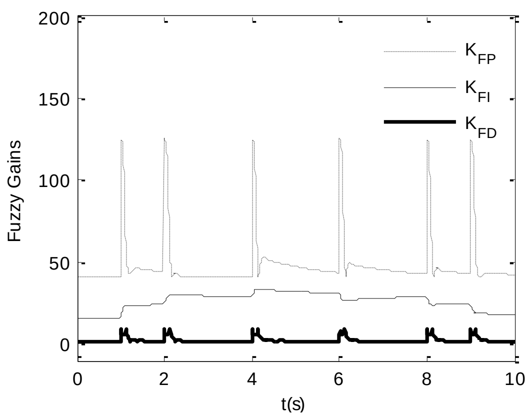


Figure 8. Variation of fuzzy PID gains

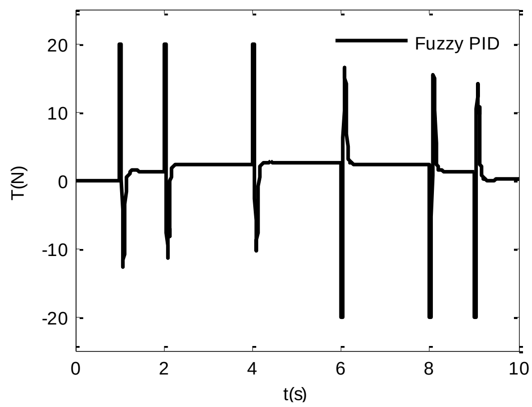


Figure 9. Thrust force

Thrust force applied by fuzzy PID controller is shown in Figure 9. The thrust force is saturated at the very beginning of ascending and descending positions during maximum position errors occur. When the controller generates a thruster force greater than the saturation value of the motorized propeller, it is limited to ±20 N. The thrust force reaches to a steady state value that holds the pendulum at the desired position as the position error goes to zero. In Figure 10, the external disturbance force acted on propeller pendulum is shown. Sine function is utilized to form external disturbance whose amplitude and frequency are 0.5 N and 1 Hz at 5 N bias.

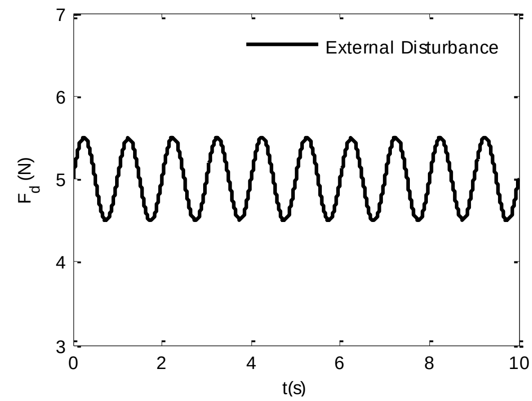
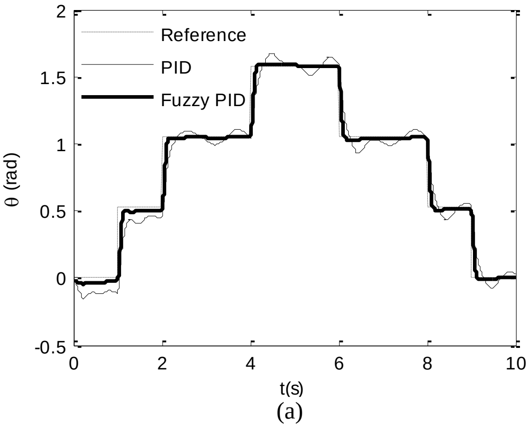
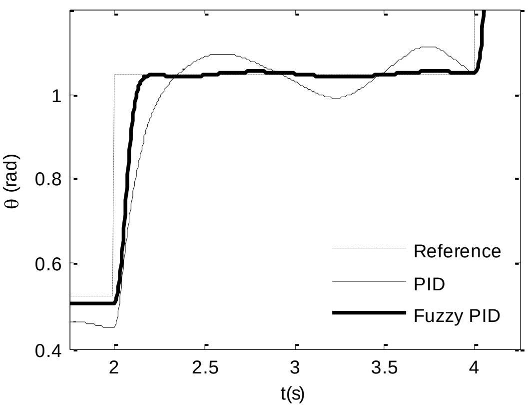


Figure 10. External disturbance

At this point, simulation results for the external disturbance applied case are given for the same reference tracked in the previous simulation in order to evaluate the performance of control under external disturbances. In the first one second duration, pendulum moves to negative direction under the effect of external disturbance in Figure 11 a. It is seen that the angular position of the propeller for the Fuzzy PID controlled case is much closer to the reference that is followed when it is compared with the classical PID controlled case in Figure 11 a and b.



(a)



(b)

Figure 11. Angular position of propeller pendulum a) for 10 s duration b) between 1.75 s and 4.25 s

If the angular position of the pendulum is compared with the previous simulation given in Figure 6 a and b, it is easy to spot the track performance loss of the classical PID controlled case which is much worse by the disturbance. On the other hand, the Fuzzy PID controlled case still follows the reference as close as the previous simulation that can also be observed from the error of angular position diagram shown in Figure 12.

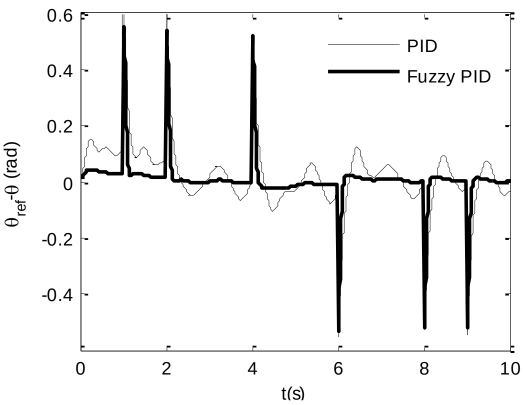


Figure 12. Error of angular position

As the pendulum moves to the negative direction at the beginning of the simulation under the effect of external disturbance, the proposed controller gives a sudden response pulling the pendulum as close as to the reference that can be seen in Figures 11 a and 14. Also, the change of fuzzy proportional gain in the first one second duration is observed in Figure 13 when compared with Figure 8.

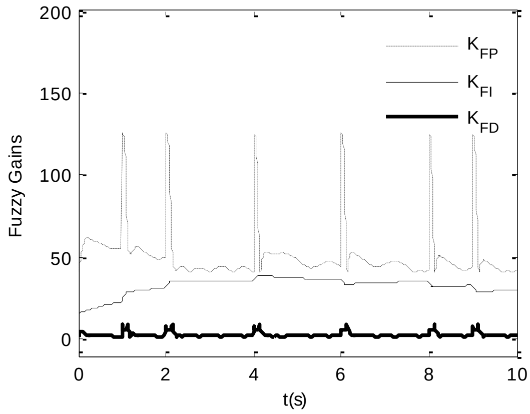


Figure 13. Variation of fuzzy PID gains

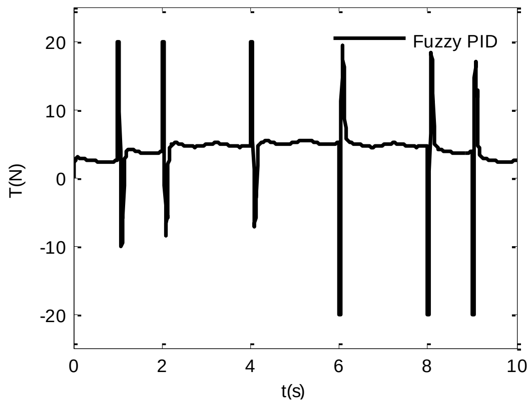


Figure 14. Thrust force

The reference tracking success of the proposed controller can also be determined from the root mean square (RMS) error comparisons given in Table 4. Case 1 and 2 represent without and with external disturbance cases respectively. In all cases, total RMS errors of fuzzy PID controller is less than PID controller ones. Total RMS thrust force values of all cases are also given in the same table. Although the thrust force need for fuzzy PID controller is greater than PID controller in all cases, the change in RMS error of fuzzy PID controller is less comparing to PID controller ones.

Table 4. RMS error and RMS thrust force comparisons

	Case 1		Case 2	
	PID	Fuzzy PID	PID	Fuzzy PID
e_{RMS}	0.115	0.091	0.130	0.094
T_{RMS}	3.275	4.473	5.028	5.882

5. Conclusions

A Fuzzy PID controller is designed and applied to a nonlinear propeller pendulum. The proposed controller which compensates the nonlinear character of the system is obtained from classical PID controller by fuzzy inference generated time varied gains. The nonlinear behavior of the system is characterized from position error, integral of position error and derivative of position error of the controlled system. Therefore, the proposed controller has encountered the angular position control issue without linearizing nonlinear system. As a conclusion, the proposed fuzzy PID controller shows better and satisfactory control performance against external disturbance for nonlinear system compared to classical linear PID controller.

6. References

[1] A. Farmanbordar, N. Zaeri and S. Rahimi, "Stabilizing a Driven Pendulum Using DLQR Control", in *2011 Fifth Asia Modelling Symposium*, 2011, pp. 123-126.
[2] A. Mohammadbagheri and M. Yaghoobi, "A New Approach to Control A Driven Pendulum with PID Method", in *2011 UKSim 13th International Conference on Modelling and Simulation*, 2011, pp. 207-211.
[3] H. Kizmaz, S. Aksoy and A. Muhurcu, "Sliding mode control of suspended pendulum", Modern Electric Power Systems (MEPS), in *2010 Proceedings of the International Symposium*, 2010, pp. 1-6.
[4] G. Habib, A. Miklos, E. T. Enikov, G. Stepan and G. Rega, "Nonlinear model-based parameter estimation and stability analysis of an aero-pendulum subject to digital delayed control", *International Journal of Dynamics and Control*, 2015, DOI 10.1007/s40435-015-0203-0.
[5] S. Srinivasulu Raju, T.S. Darshan and B. Nagendra, "Design of Quadratic Dynamic Matrix Control for Driven Pendulum System", *International Journal of Electronics and Communication Engineering*, Vol. 5, No. 3, pp. 363-370, 2012.
[6] M. Yoon, "Stabilization of a Propeller - Driven Pendulum", *International Journal of Engineering Research & Technology (IJERT)*, Vol. 5, Iss. 1, pp. 230-233, 2016.
[7] R. Ghasemi, M. R. Rahimi Khoygani, "Designing Intelligent Adaptive Controller for Nonlinear Pendulum Dynamical System", *International Journal of Computer, Electrical, Automation, Control and Information Engineering*, Vol. 8, No. 11, pp. 2021-2025, 2014.
[8] T. Huba, T. Malatinec, M. Huba, "Propeller-Pendulum for Nonlinear UAVs Control", *iJOE*, Vol. 9, Issue 1, pp. 42-46, 2013.
[9] E.T. Enikov, V. Polyzoev, J. Gill, "Low-Cost Take-Home Experiment on Classical Control Using Matlab/Simulink Real-Time Windows Target", in *Proceedings of the 2010 American Society for Engineering Education Zone IV Conference*, 2010, pp. 1-9.
[10] M.R.R. Khoygani, R. Ghasemi, D. Sanaei, "Design Controller for a Class of Nonlinear Pendulum Dynamical System", *International Journal of Artificial Intelligence*, Vol. 2, No.4, pp. 159-168, 2013.
[11] Y. Gültekin and Y.Taşcıoğlu, "Pendulum Positioning System Actuated by Dual Motorized Propellers", in *6th International Advanced Technologies Symposium*, 2011, pp. 6-9.
[12] O. Karasakal, E. Yeşil, M. Güzelkaya, I. Eksin, "Implementation of a new self-tuning fuzzy PID controller on PLC", *Turkish Journal of Electrical Engineering*, Vol. 13, No. 2, pp. 277–286, 2005.
[13] H. B. Kazemian, "Developments of fuzzy PID controllers", *Expert Systems*, Vol. 22, No. 5, pp. 254-264, 2005.
[14] J.Y. Kim, H.M. Kim, S.K. Kim, J.H. Jeon, H.K. Choi, "Designing an Energy Storage System Fuzzy PID Controller for Microgrid Islanded Operation", *Energies*, Vol. 4, pp. 1443-1460, 2011.

Note:

Yener Taskin received the BS and MS degrees in 1996 and 1999 from the Department of Mechanical Engineering of Istanbul University and the Ph.D. degree in 2008 from the Department of Mechanical Engineering of Yildiz Technical University, Istanbul. He is currently an Assistant Professor and Head of Mechatronics Division in the Department of Mechanical Engineering of Istanbul University. His research interests include mechatronics, non-linear control theory, modeling and control of vehicle vibrations.