Virtual Laboratory for Sliding Mode and PID Control of Rotary Inverted Pendulum

METIN DEMIRTAS,[1] YUSUF ALTUN,[1] AYHAN ISTANBULLU[2]

[1] *Department of Electrical and Electronics Engineering, Balikesir University, Balikesir, Turkey*

[2] *Department of Computer Engineering, Balikesir University, Balikesir, Turkey*

Received 9 June 2009; accepted 1 August 2010

ABSTRACT: This paper presents a new virtual laboratory tool which teaches sliding mode control (SMC) and proportional–integral–derivative (PID) control to graduate students. Additionally, it describes performance differences between two control methods graphically. This educational virtual laboratory tool contains the control of rotary inverted pendulum. This system is a typical example of nonlinear and under-actuated systems and also well-known in control engineering for practicing different control theories. At first, the nonlinear dynamic equations of the inverted pendulum are presented. Then a virtual laboratory tool is designed for SMC and PID. After that, the results are analyzed. The validity of designed tool is verified by an experiment. © 2010 Wiley Periodicals, Inc. Comput Appl Eng Educ 21: 400–409, 2013; View this article online at wileyonlinelibrary.com/journal/cae; DOI 10.1002/cae.20484

Keywords: rotary inverted pendulum; virtual laboratory; sliding mode control; PID control

INTRODUCTION

The inverted pendulum is a state-of-the-art plant in control education, which is useful for illustrating how to design controller for swing-up and balance. Most control strategies are applied in the linear and nonlinear control systems. Rotary inverted pendulum (RIP) problem, especially, is well-known as an example of nonlinear and under-actuated systems. Therefore, the control of RIP systems is commonly studied in control areas [1–5].

Sliding mode control (SMC) is robust control for nonlinear and linear feedback control method, which has been developed and applied to nonlinear feedback control systems around more than three decades. SMC approach has been widely used for control design problem [6,7]. SMC is one of the effective nonlinear robust control approaches since it provides desired system dynamics with an invariance property to uncertainties once the system dynamics are controlled in the sliding mode [8–11]. SMC is designed so that the system trajectories move onto a sliding surface in a finite time and tends to an equilibrium point along this surface [12].

Nowadays, some experimental setups are expensive and cannot be enable their parameter changes such as inverted pendulum systems, dc and ac motors. Therefore, the virtual laboratory is quite significant in order to observe the effects of controller parameters. In particular, understanding the systems which do not have experiment setups well is difficult in teaching. Additionally, in the education of these toll sets, understanding the effects of the controller parameters on the system by the students is difficult since the students cannot observe the parameters effects in mathematical equations. In recent years, development of virtual laboratory has received considerable attention in the literature [13–18]. There are studies about educational tools for many systems [19–22]. Besides, cart-inverted pendulum system, fixed base inverted pendulum system and cart-on-track system is studied using matlab/visual C++ [23].

LabVIEW simplifies the scientific computation, process control, research, industrial application, and measurement applications, because it has the flexibility of a programming language combined with built-in tools designed specifically for test, measurement, and control [24,25]. LabVIEW is an ideal choice for pragmatic teaching and learning. It supports and serves a wide variety of needs for test, measurement, control, and automation applications [26]. The utilization of virtual tools for teaching and learning in engineering has been well accepted by many researchers [27,28].

There are many studies on the control education. Most of them used proportional–integral–derivative (PID) controller [29]. A developed tool is used in PID education [30]. E-learning tool based on Matlab has been developed [31]. It is used PID controller in the system.

SMC is almost not used in the training aim although it is more used in the applications. This study includes two different control approaches; SMC and PID. Therefore, the designed approach is novelty in the literature.

Correspondence to M. Demirtas (mdtas@balikesir.edu.tr).

In this study, educational software is developed for SMC and PID control of RIP using LabVIEW. It is a part of a virtual control laboratory project for RIP carried out by the authors. The software can be easily used by graduate students in control courses. This tool provides a low-cost solution for laboratory experiments. The tool has a flexible structure and graphical user interface, which permits the design of the SMC and PID control system. The control performance of the controllers (PID and SMC) can be monitored according to different parameters of controllers. It helps students, instructors and researchers about SMC, PID and RIP.

DYNAMIC MODEL OF RIP SYSTEM

RIP system consists of two rods. The first rod is rotated by dc motor. The second rod is connected to the first rod. Figure 1 shows RIP system. The nonlinear dynamic equations of the inverted pendulum system are given in Equations (1) and (2) [29].The parameter definitions of the RIP control system is given in Table 1. The controller parameters are defined in SMC and PID Control of RIP Section.

$$\ddot{\theta}(m_2L_1^2 + J_1) = u - m_2l_2L_1\left(\ddot{\beta}\cos\beta - \dot{\beta}^2\sin\beta\right) - r_1\dot{\theta} \tag{1}$$

$$\ddot{\beta}(m_2l_2^2 + J_2) = m_2l_2g\sin\beta + m_2l_2L_1\left(\dot{\beta}\dot{\theta}\sin\beta - \ddot{\theta}\cos\beta\right) - r_2\dot{\beta} \tag{2}$$

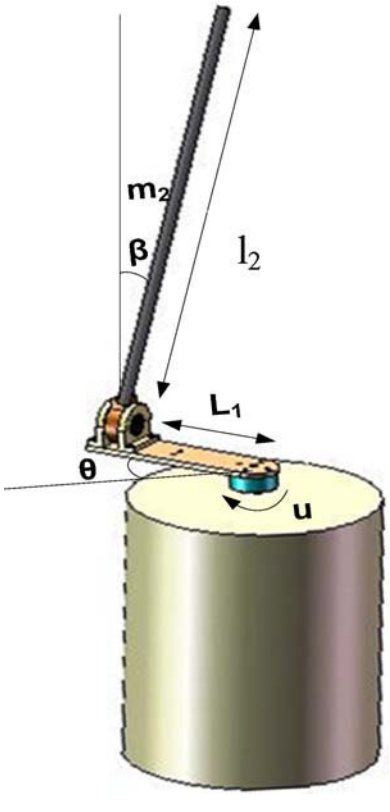


Figure 1 Rotary inverted pendulum system. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 1 Parameter Definition of the RIP

m_2	Mass of the second rod
L_1	Length of the first rod
l_2	Length of the second rod
θ	Horizontal angular displacement of the first rod
g	Gravitational acceleration
β	Vertical angular displacement of the second rod
r_1	Viscous friction coefficient of the first rod
r_2	Viscous friction coefficient of the second rod
J_1	Inertia moment of the first rod
J_2	Inertia moment of the second rod
u	Horizontal control signal of the first rod
V_m	Motor voltage
n_m	Motor efficiency
n_g	Gearbox efficiency
K_t	Motor torque constant
K_g	Motor gear ratio
K_m	Back electromotive force (EMF) constant
R_m	Armature resistance.
β_d	Desired angle of the RIP

where u is

$$u = \frac{n_m n_g K_t K_g (V_m - K_g K_m \dot{\theta})}{R_m} \tag{3}$$

Table 1 shows the parameter definition of RIP control system.

The state space expression of the system can be written as in Equation (4) [32].

$$\left.\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f_1(x) + b_1(x)V_m \\ \dot{x}_3 &= x_4 \\ \dot{x}_4 &= f_2(x) + b_2(x)V_m \end{aligned}\right\} \tag{4}$$

where, x_i is state variable vector; $f_i(x)$ and $b_i(x)$ are the nonlinear functions of the state variables. V_m is motor voltage.

SMC AND PID CONTROL OF RIP

The desired angle of RIP is obtained using SMC and PID controller.

Sliding Mode Control

Sliding surface (s) is defined for SMC as follows.

$$s = c \cdot x_{11} + x_{22} \tag{5}$$

Here, c is positive constant defining sliding surface slope. x_{11} and x_{22} is defined as follows.

$$\left.\begin{aligned} x_{11} &= \beta_d - \beta \\ x_{22} &= \tfrac{dx_{11}}{dt} \end{aligned}\right\} \tag{6}$$

where, β_d is desired angle of the second rod. It is generally 0 in the applications but β_d can be selected for different angles. For example: If the β_d is selected 5°, designed controller can balance the second rod. The aim of the study is to control the second rod. Therefore, only β angle is controlled. The sliding surface and its derivative are obtained by combination (5) and (6).

$$\left.\begin{aligned} s &= c(\beta_d - \beta) + \tfrac{d(\beta_d - \beta)}{dt} \\ \dot{s} &= c(\tfrac{d\beta_d}{dt} - \dot{\beta}) + \tfrac{d^2(\beta_d - \beta)}{dt^2} \end{aligned}\right\} \tag{7}$$

The state in (8) must be provided for stability of the system in SMC [32].

$$\lim_{s\to 0^+} \dot{s} < 0 \quad \text{and} \quad \lim_{s\to 0^-} \dot{s} > 0 \tag{8}$$

The control signal is defined as;

$$u = U_0 \mathrm{sign}(s) \tag{9}$$

Sign stands for signum function defined as in Equation (10).

$$\mathrm{sign}(s) = \begin{cases} 1 & s > 0 \\ 0 & s = 0 \\ -1 & s < 0 \end{cases} \tag{10}$$

If a saturation function is used in place of sign function, the chattering problem is eliminated [33].

PID Control

PID controller structure is the most widely used in industrial control systems. It is pointed out that more than 95% of the controllers used in process control applications are of PID-type. Here, *P*, *I*, and *D* are controller's gains [34,35].

THE VIRTUAL LABORATORY ARCHITECTURE

The architecture of the virtual laboratory system and designed virtual laboratory tool are shown in Figure 2. The client computers communicate with the server computer and display the designed virtual laboratory on their screen via Internet.

The client computers run a web browser and open a web page loaded from the server. Therefore, the remote users do not need any other special software installed on their machine except LabVIEW player program. By this tool, students can access to virtual learning environment and make virtual experiments. They can observe the process outputs graphically on their computer screen.

THE DESIGNED EDUCATIONAL TOOL

The tool enables the instructors to teach SMC and PID control of RIP to students without spending more time. The outputs of the system can be observed on the computer screen when the instructors click the mouse. The students can see the outputs and comment the results in the class. Since they can see each parameter effect graphically, they can easily understand SMC, PID control, and RIP. They can also study on this control system using the Internet.

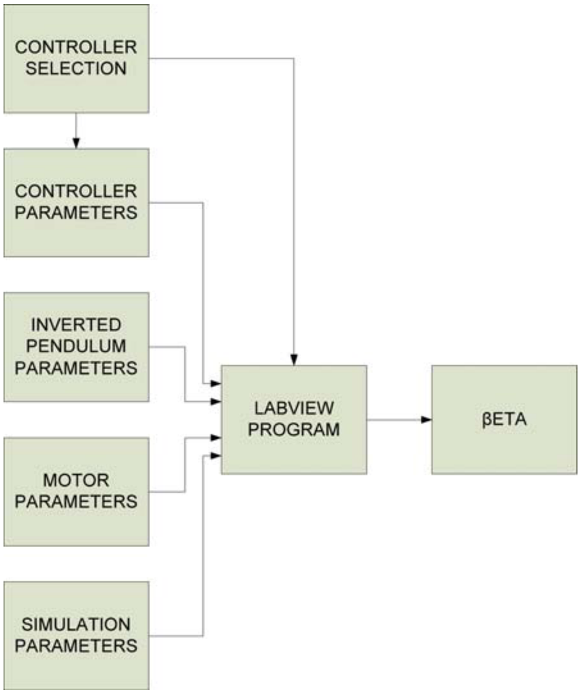


Figure 3 The block diagram of the educational tool.

This tool helps to researchers who will practice the control of RIP because they can change inverted pendulum parameters and determine the dc motor parameters on the parameters screen. They also may develop new ideas. Moreover, they will gain time for their researches. Figure 3 shows the block diagram of the tool designed using LabVIEW.

Figure 4 shows parameters screen which is a part of LabVIEW graphical user interface screen front panel in Figure 2. The inverted pendulum parameters, controller type and controller

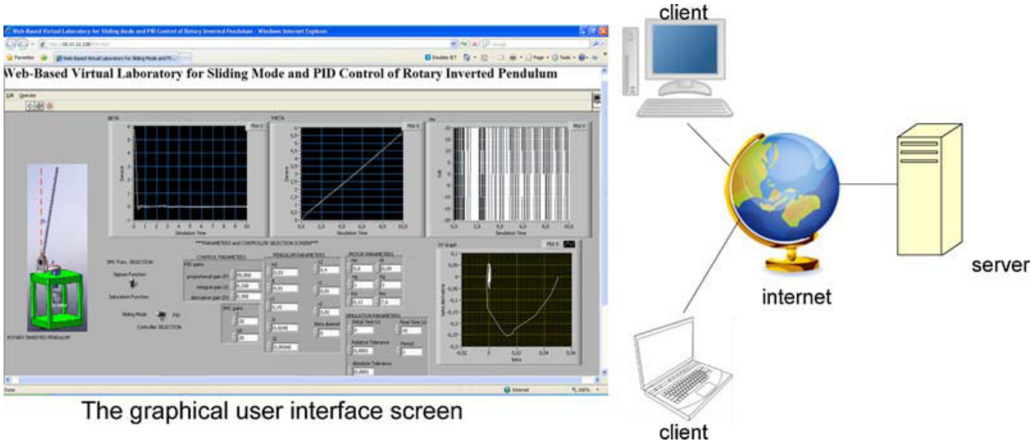
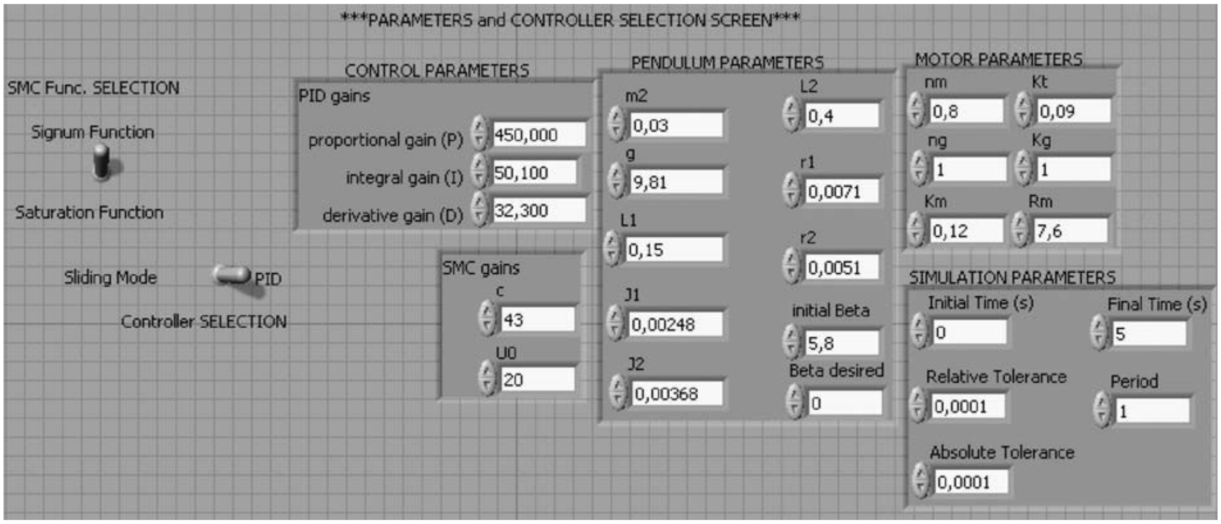


Figure 2 Virtual laboratory architecture. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]



PARAMETERS and CONTROLLER SELECTION SCREEN

SMC Func. SELECTION: Signum Function / Saturation Function

Sliding Mode / PID — Controller SELECTION

CONTROL PARAMETERS

PID gains
proportional gain (P) 450,000
integral gain (I) 50,100
derivative gain (D) 32,300

SMC gains
c 43
U0 20

PENDULUM PARAMETERS
m2 0,03
g 9,81
L1 0,15
J1 0,00248
J2 0,00368
L2 0,4
r1 0,0071
r2 0,0051
initial Beta 5,8
Beta desired 0

MOTOR PARAMETERS
nm 0,8
Kt 0,09
ng 1
Kg 1
Km 0,12
Rm 7,6

SIMULATION PARAMETERS
Initial Time (s) 0
Final Time (s) 5
Relative Tolerance 0,0001
Period 1
Absolute Tolerance 0,0001

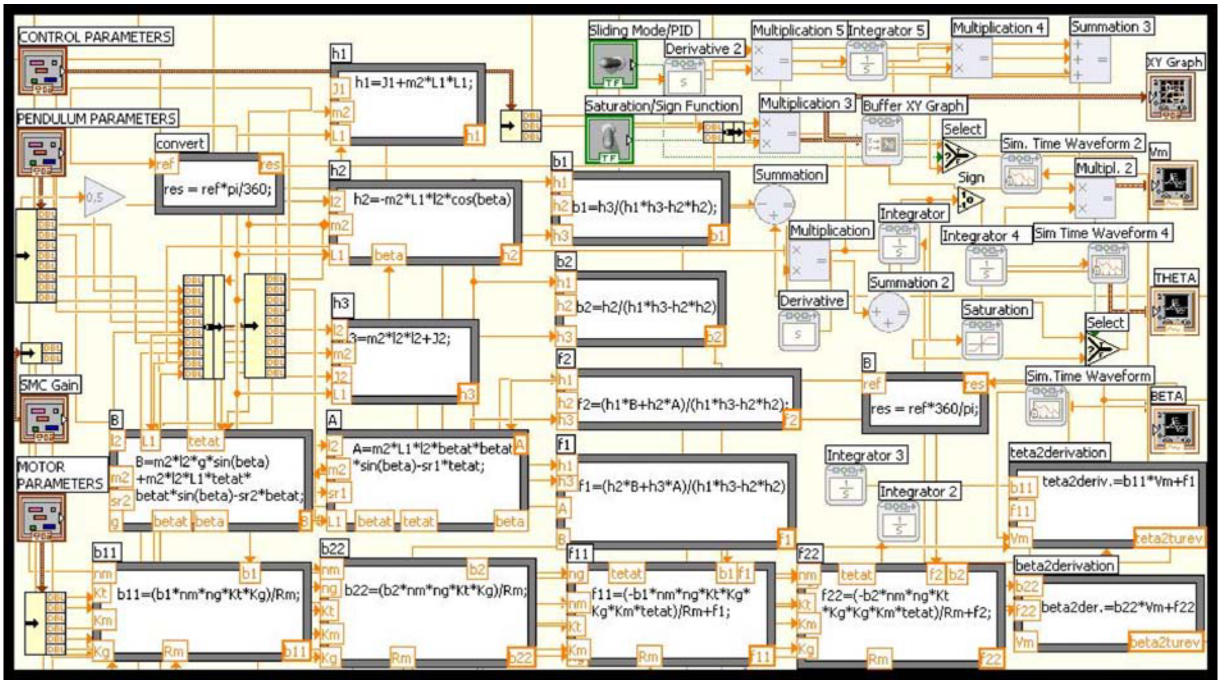
Figure 4 Parameters and controller selection screen.

parameters are given on parameters screen. Block diagram of the virtual laboratory of LabVIEW is shown in Figure 5.

LabVIEW allows graphical programming. The equations (f_{11}, f_{22}, etc.) can be written in boxes as seen in the Figure. Operators like integration, derivation, and the other functions can be easily used in block diagram. Binary switch can be used to select SMC or PID controller. Likely, the second switch is used to select the saturation or signum functions. The parameter inputs of the graphical interface is seen on the left part of the block diagram. The graphical outputs is shown on the right part of the block diagram.

The tool has many advantages. For instance, the tool enables to change all of the system parameters; simulation parameters, control parameters, RIP parameters, and motor parameters. Hence, the users can observe the parameter effects on the inverted pendulum graphically. For example, if the users increase period time on parameters screen, control system runs slowly. Thus, the graphic of the process output is drawn slowly on the screen. Similarly, the sensitivity of the simulation can be changed by changing the values of the relative and absolute tolerance on parameters screen.

As shown in Figure 4, the users can change the function (saturation or signum) using "SMC function selection switch." They can also select SMC or PID controller by "controller selection switch." Furthermore, the parameters of the controller can be changed via the tool interface. Thus, students can observe the effects of inverted pendulum system parameters and controller parameters on the system.



```
h1=J1+m2*L1*L1;
h2=-m2*L1*l2*cos(beta)
3=m2*l2*l2+J2;
res = ref*pi/360;
b1=h3/(h1*h3-h2*h2);
b2=h2/(h1*h3-h2*h2)
f2=(h1*B+h2*A)/(h1*h3-h2*h2);
f1=(h2*B+h3*A)/(h1*h3-h2*h2)
B=m2*l2*g*sin(beta)
+m2*l2*L1*tetat*
betat*sin(beta)-sr2*betat;
A=m2*L1*l2*betat*betat
*sin(beta)-sr1*tetat;
res = ref*360/pi;
b11=(b1*nm*ng*Kt*Kg)/Rm;
b22=(b2*nm*ng*Kt*Kg)/Rm;
f11=(-b1*nm*ng*Kt*Kg*
Kg*Km*tetat)/Rm+f1;
f22=(-b2*nm*ng*Kt
*Kg*Kg*Km*tetat)/Rm+f2;
teta2deriv.=b11*Vm+f1
beta2der.=b22*Vm+f22
```

Figure 5 Block diagram of the virtual laboratory of LabVIEW. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

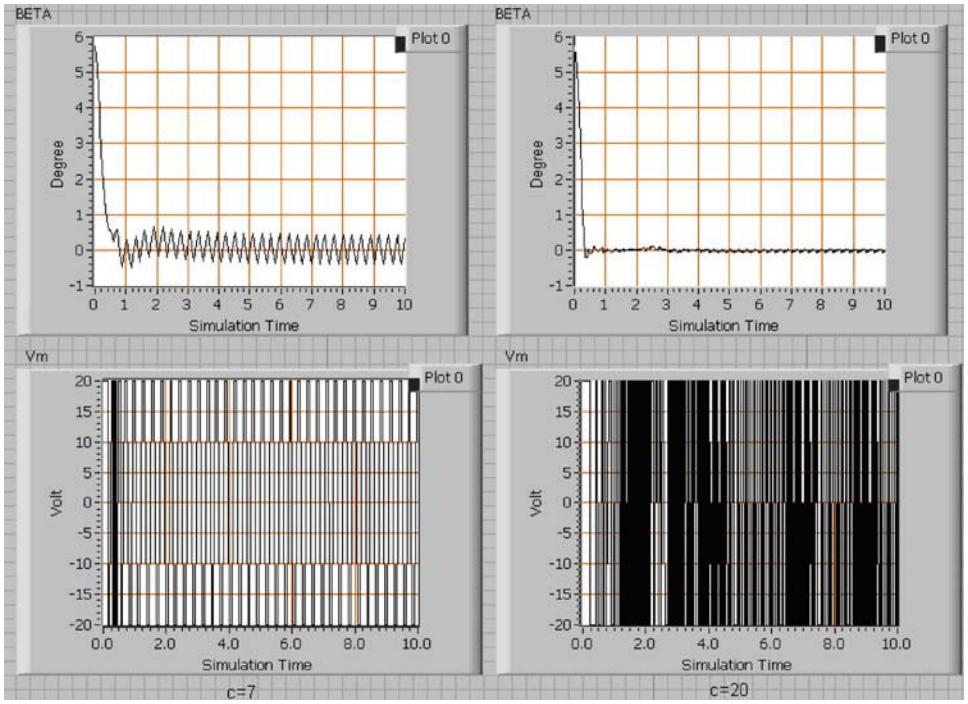


Figure 6 The outputs of the control system for signum function in SMC ($c = 7$ and $c = 20$). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

PID controller coefficients are quite important for the control system. Therefore, the effectiveness of P, I, and D coefficients on RIP control system can be observed and analyzed by designed educational tool packet. Similarly, the choice of c coefficient is crucial for SMC. c must be determined very well due to the fact that it affects the system stability. The system outputs can be observed by changing the parameter coefficients of two controllers. Thus, the effects of controller coefficients can be analyzed using the tool. This provides simplicity for users. The relation between controllers and pendulum can be seen.

Consider the problem of teaching sliding mode and PID controller. During the course, the instructors have a limited amount of time to explain and illustrate the results of SMC. Often the students ask for understanding the effectiveness of the parameter changes on the sliding mode and PID controller.

RESULTS AND DISCUSSION

Educational tool results of SMC and PID controller are given for different parameters. RIP and motor parameters in Figure 4 are used for simulation studies. Figure 6 shows results of SMC for different c values which affect the system dynamics.

As shown in Figure 6, while c is 20, β reaches to β_d in a short time. β angle oscillates around β_d, while the value of c is 7. The effect on the system stability of c is by analyzed changing the value of c. The users can understand the effect of c on the system.

Figure 7 shows results of SMC for signum and saturation functions. The user can observe the elimination of the chattering problem in SMC by selecting saturation function in tool screen. All of the initial conditions are taken for $\theta = 0^\circ$. As shown in Figures 6–12, β and V_m are observed by changing the controller parameters on parameters screen of the tool.

As shown in Figure 7, β and V_m graphics are obtained using saturation and signum function with the same c value. The chattering occurs as shown on the control signal (V_m) because of signum function. While saturation function is used in place of signum function, no chattering problem occurs on V_m. Thus, the users can easily understand the chattering problem in SMC. The chattering is a disadvantage and distinguished characteristic for SMC according the other controllers.

Figure 8 shows the results of both SMC and PID control. Using different SMC and PID control parameters, two control methods can be compared by users in view of performance of settling time, overshoot, and rising time.

PID is a linear approach for the nonlinear system. The solution of PID controller is good in linear system. But, the used inverted pendulum system is nonlinear. As shown in Figure 8, both SMC and PID controller are very good at the desired angle 0°. The desired angle is chosen -1° and 5°, to compare two controllers. The system response is bad when PID controller is used for balancing the rod, as shown in Figure 9. System output is not settling down the desired value, but when SMC is applied the same system, as shown in Figure 10, system output is settling down at the desired reference ($\beta = -1^\circ$). That is, when PID controller is used, the rod is not brought into balance at -1°, while the rod is brought into balance at 0°. The rod is brought into balance at different desired angle values (0° or -1°) when SMC is applied to the same system.

Similarly, the system is simulated while initial angle is 0 and desired angle is 5°. The response of SMC is very good according to PID controller as shown in Figures 11 and 12. The rod is not brought into balance at desired angle ($\beta = 5^\circ$) when PID controller is used as shown in Figure 11. The result of the SMC is good at desired angle ($\beta = 5^\circ$), although L_1 (length of the rod) is changed to 0.3 m. So, SMC is advantageous against disturbance

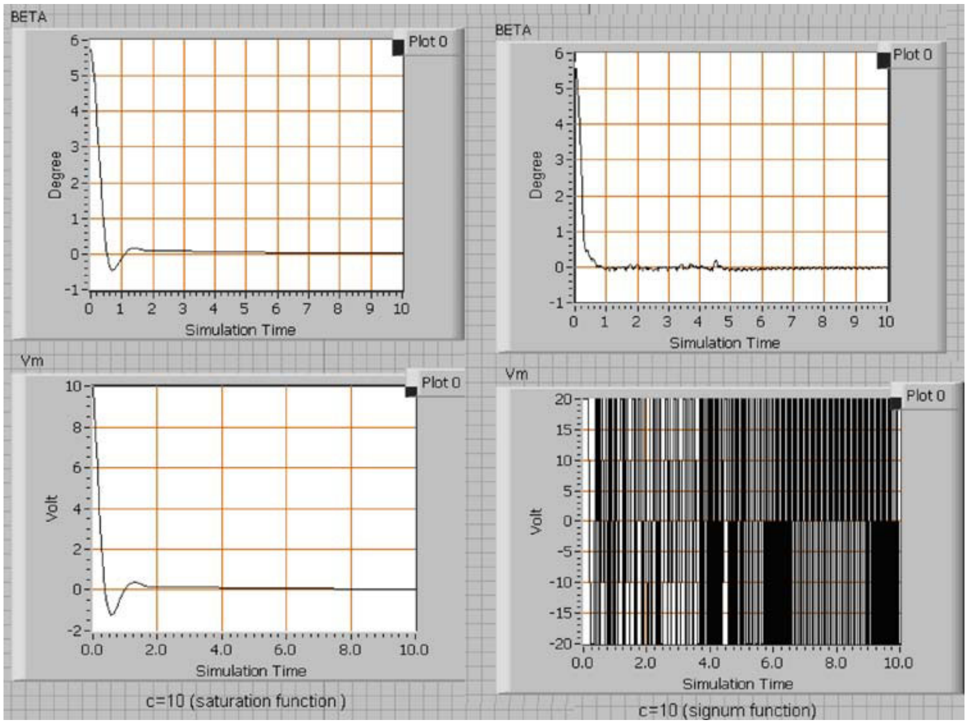


Figure 7 The outputs of the control system for saturation and signum functions in SMC ($c = 10$). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

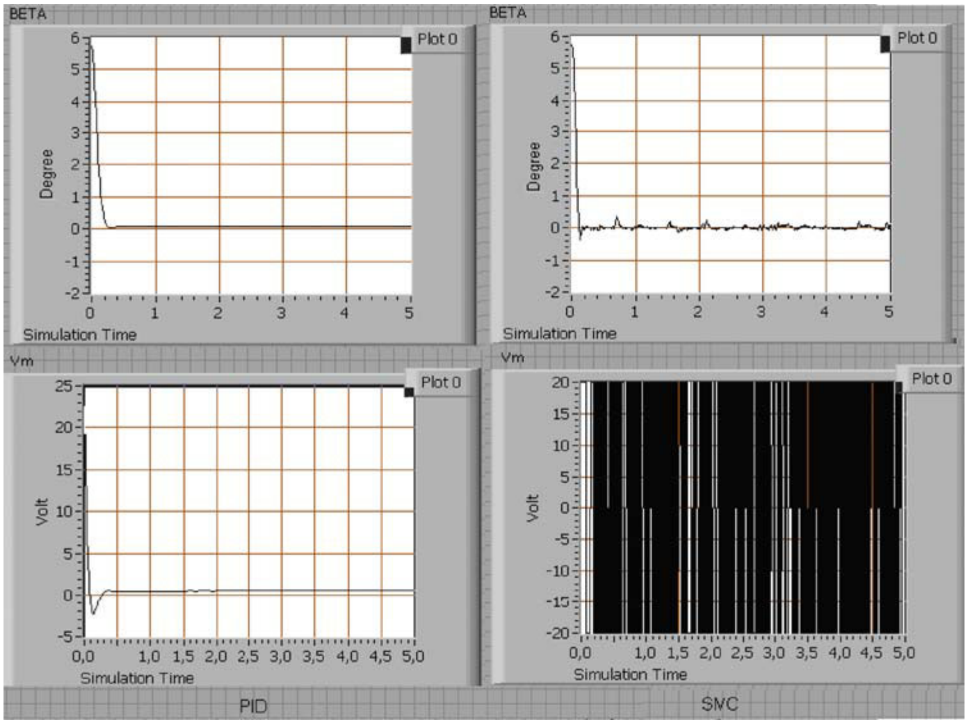


Figure 8 The outputs of SMC and PID control (desired angle $\beta = 0^{\circ}$). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

and parameters changes as compared to PID. Therefore it is known as robust. Disadvantage of SMC is the chattering problem. This problem can be eliminated by using saturation function (Figure 7), fuzzy boundary layer [33] or boundary layer [36].

RIP system is carried out as an experimental setup at Balıkesir University for showing the confirmation of the designed tool. The experimental setup is given in Figure 13. Obtained result from the experimental setup is demonstrated in Figure 14 for indicating chattering problem [32]. Here, signum function was used as control signal. The results in Figures 6–8 are similar in point of chattering. So, the validity of designed tool is verified. The angle of the pendulum is measured with a potentiometer, and the speed of the motor with an encoder.

EVALUATION

In order to test the efficiency of this new tool, a survey which includes five questions has been carried out in Electrical Engineering Department of Balikesir University. The number of the graduate students involved in the survey is 20 (n), between 2006 and 2008 years.

In order to test the efficiency of this new approach, students have been asked the following questions:

1. Was the learning process with the tool successful?Fifteen of 20 participants answered yes, the rest of students answered no (yes: 75%, no: 25%); majority of the students who found

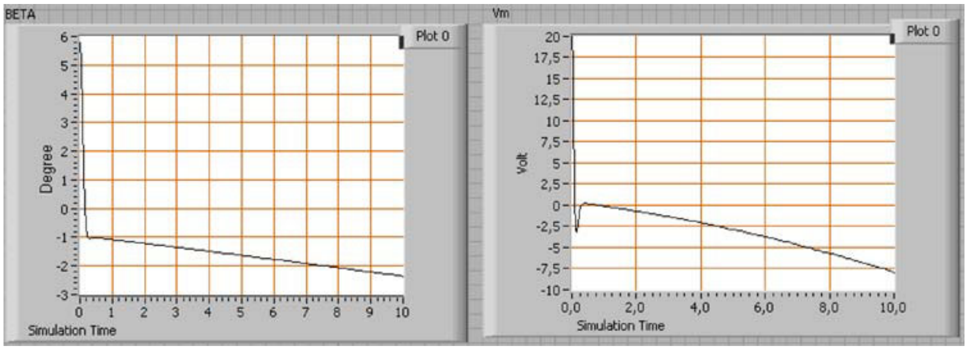


Figure 9 The output of the PID controller (initial angle is 5.8°, desired angle is −1°). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

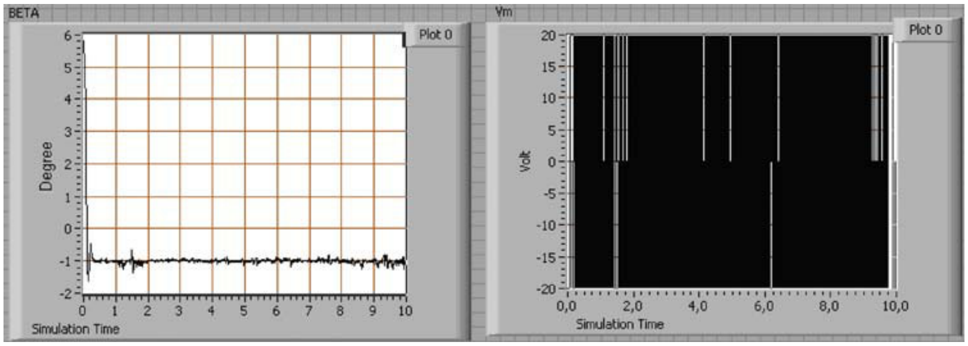


Figure 10 The output of the SMC controller (initial angle is 5.8° and desired angle is −1°). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

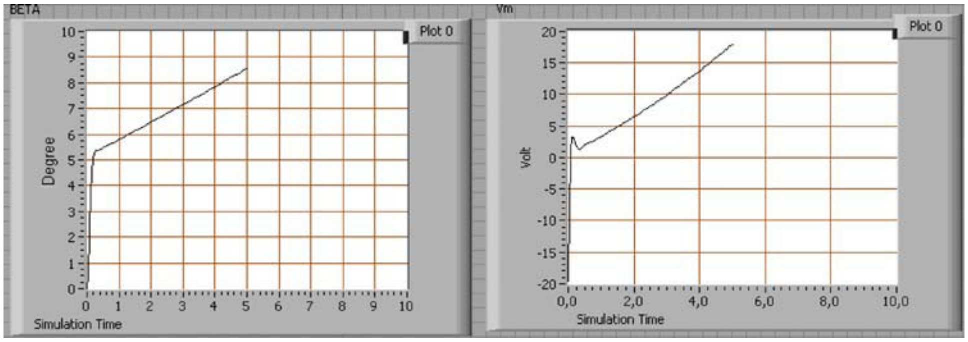


Figure 11 The output of the PID controller (initial angle is 0° and desired angle is 5°). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

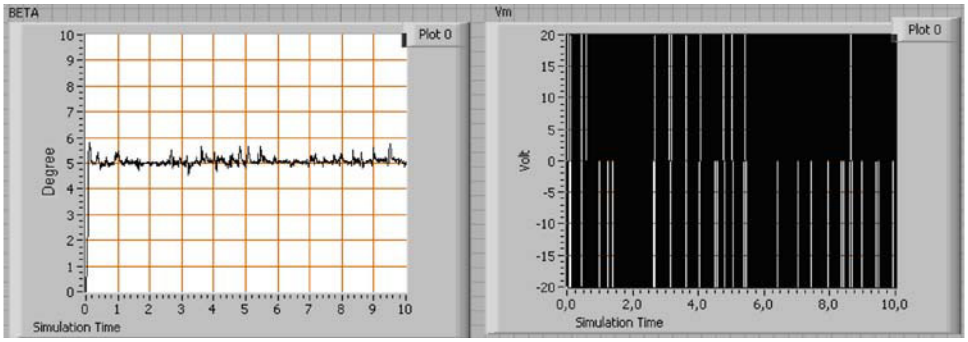


Figure 12 The output of PID controller (L_1 is 0.3 m, initial angle is 0° and desired angle is 5°). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 13 The experimental setup of RIP. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

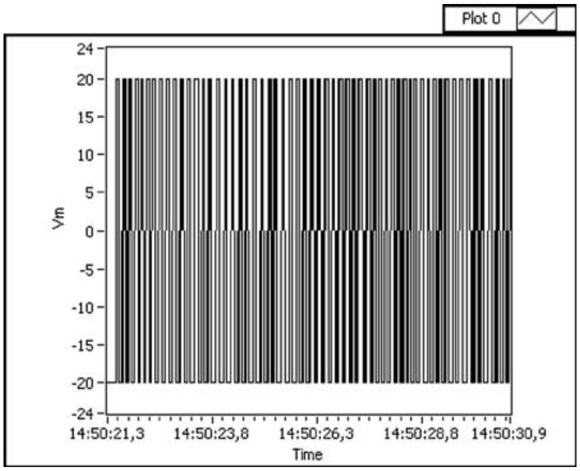


Figure 14 V_m output of SMC in real experiment.

the system effective stated that they liked the use of virtual laboratory as an educational tool.

2. Is the virtual laboratory user interface useful?Yes: 50%, No: 40%, no answer: 10%.Half of the students found that it is useful for the course. Some of them considered that the graphical interface of the tool is complex. They suggested that the inverted pendulum parameters and controller parameters should be on different screens.
3. Do you understand the effects of P, I, D, and c coefficients to system?Yes: 90%, No: 10%.P, I, and D coefficients are changed separately. Similarly c coefficient is also changed. The settling time, overshoot, and rising time of the system is observed. Hence, students stated that they observed the performance of the controllers.
4. Do you understand the differences between PID control and SMC?Yes: 80%, No: 20%.Students stated that there are three coefficients in PID control and there is one coefficient in SMC. Therefore, SMC is advantageous when compared to PID in view of the optimization of the coefficients. Students said that there is a chattering problem in SMC. PID is advantageous in view of chattering compared to SMC. SMC eliminates disadvantage using saturation function in place of signum function. There is one coefficient which is affecting the system dynamic response in SMC. There are three coefficients effecting system behaviors.
5. (a) Do you observe chattering problem? Yes: 80%, No: 20%. (b) Do you observe elimination of chattering problem when saturation function is used? Yes: 75%, No: 25%.Students stated that they observed the chattering problem using SMC function selection switch on the designed tool. Many of the students said that chattering problem is eliminated in the control signal using controller selection switch.Success and motivation of the students increased after the tool was used in the course. Many students explained that their learning process was successful after using this tool. Some students suggested that the chattering problem can be eliminated using low pass filter and some trigonometric functions. They said that the system can also be useful for students at undergraduate levels.

CONCLUSION

In this paper, an educational virtual laboratory tool is designed for sliding mode and PID control of RIP using LabVIEW. The tool enables users to change parameters of RIP controller and motor. The user interface shows the outputs of control systems graphically. This tool helps students to understand SMC and PID control of RIP. Without a real laboratory setup, students can practice from their home using this tool. The main objective behind the virtual laboratory development project was to allow graduate students without any programming experience about sliding mode and PID control of RIP control system. Students can evaluate the differences between PID and SMC in terms of performance. They can also determine the best coefficients changing controller parameters. This tool can also be useful for undergraduate students at control Engineering Department.

The instructors gain time for their researches because they will need a shorter teaching period. They teach the control techniques (SMC and PID control) to their graduate students using computers. The parameter effects of sliding mode and PID controllers can be thought by more examples in a short time. In addition, this tool helps researchers who will conduct a real experimental practice. They can change inverted pendulum parameters on parameters screen and determine dc motor parameters for real experimental practice. Therefore, researchers will gain time for experimental research. Moreover, they obtain simulation results of the control of RIP system.

This tool can be used for automatic control, nonlinear control, SMC, feedback control courses. Many Engineering Departments (electrical, control, mechatronic, and mechanical) can use this tool for teaching SMC and PID control. In this study, the designed approach is a novelty from the point of control education.

ACKNOWLEDGMENTS

This study was supported Balikesir University Scientific Research Projects (BAP-2008/09).

REFERENCES

[1] M. E. Magana and F. Holzapfel, Fuzzy-logic control of an inverted pendulum with vision feedback. IEEE Trans Educ 41 (1998), 165–170.

[2] W. Rekdalsbakken, Feedback control of an inverted pendulum with the use of artificial intelligence computational cybernetics. J Adv Comput Int Int Inform 11 (2007), 1114–1121.

[3] M. A. Khanesar, M. Teshnehlab, and M. A. Shoorehdeli, Sliding mode control of rotary inverted pendulum, Mediterranean Conference on Control & Automation, 27–29 June 2007, pp. 1–6.

[4] W. Jun-feng and L. Chun-tao, Robust output-feedback control of inverted pendulum, Industrial Electronics and Applications, ICIEA 2nd IEEE Conference, 23–25 May 2007, pp. 1027–1030.

[5] M. A. Teshnehlab, M. Shoorehdeli, and M. A. Khanesar, Fuzzy sliding mode control of rotary inverted pendulum, IEEE International Conference on Computational Cybernetics, 19–21 October 2007, pp. 57–62.

[6] O. Kaynak, K. Erbatur, and M. Ertugrul, The fusion of computationally intelligent methodologies and sliding-mode control-A survey. IEEE Trans Ind Electron 48 (2001), 4–12.

[7] V. M. Panchade, L. M. Waghmare, B. M. Patre, and P. P. Bhogle, Sliding mode control of DC drives, Mechatronics and Automation 2007 International Conference, 5–8 August 2007, pp. 1576–1580.

[8] V. I. Utkin, Sliding mode control design principles and applications to electric drives. IEEE Trans Ind Electron 40 (1993), 23–36.

[9] J. J. E. Slotine and W. Li, Applied nonlinear control. Englewood Cliffs, NJ, Prentice-Hall, 1991.

[10] C. K. Lai and K. K. Shyu, A novel motor drive design for incremental motion system via sliding-mode control method. IEEE Trans Ind Electron 52 (2005), 449–507.

[11] F.-J. Lin, L.-T. Teng, and P.-H. Shieh, Intelligent sliding-mode control using RBFN for magnetic levitation system. IEEE Trans Ind Electron 54 (2007), 1752–1762.

[12] A. J. Koshkouei and A. S. I. Zinober, Sliding mode controller-observer design for SISO linear systems. Int J Syst Sci 29 (1998), 1363–1373.

[13] A. Valera, J. L. Diez, M. Valles, and P. Albertos, Virtual and remote control laboratory development. IEEE Control Syst Mag 25 (2005), 35–39.

[14] H. A. Basher and S. A. Isa, On-campus and online virtual laboratory experiments with LabVIEW, Proceedings of the IEEE Southeast Conference, March 31–April 2 2005, pp. 325–330.

[15] H. A. Basher, S. A. Isa, and M. A. Henini, Virtual laboratory for electrical circuit course, IEEE Southeast Conference Proceedings, Greensboro, North Carolina, March 26–29, 2004, pp. 330–334.

[16] C. H. Ko, B. M. Chen, V. Ramakrishnan, C. D. Cheng, Y. Zhuang, and J. Chen, A web-based virtual laboratory on a frequency modulation experiment, IEEE Trans Syst Man, and Cyber—Part C: Applications and Reviews, Vol. 31, No. 3, August 2001, pp. 295–303.

[17] M. C. Plummer, C. Bittle, and V. Karani, A circuit II laboratory accessible by Internet. Proc Am Soc Eng Educ (2002). soa.asee.org/paper/conference/paper-view.cfm?id=16769.

[18] C. Salzmann, D. Gillet, and P. Huguenin, Introduction to real-time control using LabVIEW with an application to distance learning. Int J Eng Educ 16 (2000), 255–272.

[19] L. Foulloy, R. Boukezzoula, and S. Galichet, An educational tool for fuzzy control. IEEE Trans Fuzzy Syst 14 (2006), 217–221.

[20] C. Elmas and M. A. Akcayol, PC based educational tool for a switched reluctance drive with fuzzy logic. Int J Electr Eng Educ 40 (2003), 208–219.

[21] P. Thepsatoml, A. Numsomran, V. Tipsuwanpo, and T. Teanthong, DC motor speed control using fuzzy logic based on LabVIEW, SICE-ICASE International Joint Conference, Bexco, Busan, Korea, 18–21 October 2006, pp. 3617–3620.

[22] H. Guruler, A. Istanbullu, O. N. Yigitbasi, and O. K. Ersoy, Virtual instrument application in industry and data acquisition (In Turkish), International VII. Turkish Symposium on Artificial Intelligence and Neural Networks, Canakkale–Turkey, July 2–4 2003, pp. 69–71.

[23] A. A. Rodriguez, R. P. Metzger, O. Cifdaloz, and T. Dhirasakdanon, Description of a modeling, simulation, animation, and real-time control (MoSART) environment for a class of electromechanical systems. IEEE Trans Educ 48 (2005), 359–374.

[24] D. Gillet, H. A. Latchman, CH. Salzmann, and O. D. Crisalle, Hands-on laboratory experiments in flexible and distance learning. Int J Eng Educ 90 (2001), 187–191.

[25] C. C. Ko, B. M. Chen, J. Chen, Y. Zhuang, and K. Chen Tan, Development of a web-based laboratory for control experiments on a coupled tank apparatus. IEEE Trans Educ 44 (2001), 76–86.

[26] A. See, Rapid prototyping design and implementation of a motion control integrated with an inexpensive machine vision system, IMTC—Instrumentation and Measurement Technology Conference Ottawa, Canada, 17–19 May 2005, pp. 2065–2070.

[27] A. Istanbullu and I. Guler, Multimedia based medical instrumentation course in biomedical engineering. J Med Syst 28 (2004), 447–454.

[28] M. Demirtas, Y. Altun, and A. Istanbullu, An educational virtual laboratory for sliding mode and PID control of inverted pendulum, IEEE 11th international conference on optimization of electrical and electronic equipment OPTIM'08, Brasov, Romania, 22–24 May, 2008, pp. 149–156.

[29] Z. Wang, Y. Chen, and N. Fang, Minimum-Time Swing-up of a rotary inverted pendulum by iterative impulsive control, Proceedings of the American Control Conference, Vol. 6, June 30–July 2, 2004, pp. 1335–1340.

[30] M. Huba and M. Simunek, Modular approach to teaching PID control. IEEE Trans Ind Electron 54 (2007), 3112–3121.

[31] R. Dormido, H. Vargas, N. Duro, J. Sanchez, S. Dormido-Canto, G. Farias, F. Esquembre, and S. Dormido, Development of a web-based control laboratory for automation technicians: The three-tank system. IEEE Trans Educ 51 (2008), 35–44.

[32] Y. Altun, Application of hierarchical sliding mode control to inverted pendulum systems, Master Thesis, Department of Electrical Electronics Engineering, Balikesir University, 2008.

[33] I. Senol, M. Demirtas, S. Rustemov, and B. Gumus, Position control of induction motor a new-bounded fuzzy sliding mode controller. COMPEL 24 (2005), 145–157.
[34] S. V. Ustun and M. Demirtas, Optimal tuning of PI coefficients by using fuzzy-genetic for V/f controlled induction motor. Exp Syst Appl 34 (2008), 2714–2720.
[35] S. Rustemli, M. Yilmaz, and M. Demirtas, Ripple reduction at speed and torque of step motors used on a two-axis robot arm. Robot Comput Integr Manuf (2010), DOI:10.1016/j.rcim.2010.05.003.
[36] M. Demirtaş, DSP-based sliding mode speed control of induction motor using neurogenetic structure. Exp Syst Appl 36 (2009), 5533–5540.

BIOGRAPHIES

Metin Demirtas was born in Mus, Turkey, in 1968. He received BSc degrees in electrical engineering from Yildiz University and Kocaeli University, in 1989 and 1996, respectively. He got a PhD degree in electrical engineering from Yildiz Technical University, Turkey, in 2002. He is currently at the Electrical and Electronics Engineering Department in Balikesir University in Turkey. His current research interests include power electronics, power system, electric machines and control.

Yusuf Altun was born in Karabuk, Turkey. He received the Bachelors Degree in electrical and electronics engineerings from Zonguldak Karaelmas University, Zonguldak, Turkey, in 2005. He is currently doing his PhD thesis in the Department of Control and Automation Engineering of Yildiz Technical University, Istanbul, in Turkey. Since 2008, he has been working as research assistant at the Yildiz Technical University. His research interests are in areas of control systems, intelligent control and sliding mode control.

Ayhan Istanbullu was born in Kutahya, Turkey, in 1972. He received his undergraduate degree (1993) and his PhD from the Electronic and Computer Science Education Department of the Gazi University (2003), Turkey. He worked as an instructor at the University of Mugla, Turkey, in the Department of Electronic and Computer Science Education between 2001 and 2006. He currently works as an Assistant Professor in Computer Engineering Department of Balikesir University, Turkey. He has participated in European Remote Radio Laboratory project (EU LdV) and he has acted as project partner. His current research interests include the investigation of information technologies to support electronic and computer engineering education, mobile learning and intelligent tutoring.