Real-time control and application with self-tuning PID-type fuzzy adaptive controller of an inverted pendulum

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Abstract
Purpose – This paper aims to keep the pendulum on the linear moving car vertically balanced and to bring the car to the equilibrium position with the designed controllers.

Design/methodology/approach – As inverted pendulum systems are structurally unstable and nonlinear dynamic systems, they are important mechanisms used in engineering and technological developments to apply control techniques on these systems and to develop control algorithms, thus ensuring that the controllers designed for real-time balancing of these systems have certain performance criteria and the selection of each controller method according to performance criteria in the presence of destructive effects is very helpful in getting information about applying the methods to other systems.

Findings – As a result, the designed controllers are implemented on a real-time and real system, and the performance results of the system are obtained graphically, compared and analyzed.

Originality/value – In this study, motion equations of a linear inverted pendulum system are obtained, and classical and artificial intelligence adaptive control algorithms are designed and implemented for real-time control. Classic proportional-integral-derivative (PID) controller, fuzzy logic controller and PID-type Fuzzy adaptive controller methods are used to control the system. Self-tuning PID-type fuzzy adaptive controller was used first in the literature search and success results have been obtained. In this regard, the authors have the idea that this work is an innovative aspect of real-time with self-tuning PID-type fuzzy adaptive controller.

Keywords  PID Control, Fuzzy logic control, Inverted pendulum, Real time control, Self-tuning PID-type fuzzy adaptive controller

Paper type Research paper

Nomenclature

\( P \) = Proportional Gain; \\
\( I \) = Integral Gain; \\
\( D \) = Derivative Gain; \\
\( PID \) = Proportional-Integral-Derivative; \\
\( K_p \) = Proportional control coefficient; \\
\( K_d \) = Derivative control coefficient; \\
\( K_i \) = Integral control coefficient; \\
\( \theta \) = The angle of pendulum; \\
\( \dot{\theta} \) = The angle velocity of pendulum; \\
\( x \) = The car of position; \\
\( \dot{x} \) = The car of velocity; \\
\( e \) = Angle/position error; \\
\( \dot{e} \) = Angle/position velocity error; \\
\( M \) = Mass of cart; \\
\( m \) = Mass of arm; \\
\( I \) = Moment of Inertia of pendulum; \\
\( L \) = Length of pendulum; \\
\( b \) = Cart friction coefficient; and \\
\( g \) = Acceleration due to gravity.

1. Introduction

Inverted pendulums are important engineering systems that are utilized in the solution of many engineering problems and performing motion analyses by the application of control techniques on it. Real-time balancing exercises of these systems have been quite challenging and important for modern control theory. These systems form the basis of many systems from car, aircraft, missile launcher to human gait, from luggage carrying robots to earthquake-resistant building design, etc. (Bottaro et al., 2005; Seo et al., 2007; Tsuji and Ohnishi, 2002; Zhou, 2008; Kim and Kwon, 2017). In the literature, inverted pendulum has been attempted using various methods. These are the first energy-based approaches. Depending on gravity, an
osscillatory behavior of the inverted pendulum is investigated in an energy-based approach (Aström and Furuta, 2000). In another study, the angular control of the pendulum around the equilibrium point of the pendulum system and the position control of the vehicle were carried out (Yi et al., 2001). The proportional-integral-derivative (PID) method, which is the foundation of control methods, has been practiced to these systems in diverse studies. Akole and Tyagi (2008) designed the PID conventional control method and rule-based fuzzy logic controller (FLC) and compared these two methods. They obtained very realistic outcomes in terms of the determination of PID coefficients and multiple use of the PID controllers used for controlling the inverted pendulum systems (Wang, 2011). Fuzzy logic theory was investigated by Azerbaijani Prof Lotfi A. Zadeh. In his work, Zadeh attributed the ability of people to be able to control some systems better than machines to people’s ability to make decisions by using certain information that cannot be explained in a definite way (fuzzy). Fuzzy logic operations consist of the analysis and identification of a problem, construction of variable clusters and logic relations and transformation of the knowledge gained into fuzzy sets and the interpretation of the model (Zadeh, 1965, 1968). Liu et al. (2009) obtained a mathematical model of the inverted pendulum system and used real-time fuzzy control. A fuzzy set of rules was used by Kizir and his colleagues to keep the inverted pendulum system in real-time balance (Kizir et al., 2010). Tang and others proposed and put into practice a new fuzzy- evidential controller based on fuzzy inference and evidential reasoning for the stability control of the planar inverted pendulum system (Tang et al., 2016). In another study, a PID-type fuzzy controller that performs well in overshoot, crash time, rise time, integral absolute error and robustness was designed (Ahmadi et al., 2014). Three different types of fuzzy controllers were designed by Bui et al. and applied to a damped elastic-jointed inverted pendulum system subjected to periodic follow-up force in a simulated environment (Bui et al., 2012).

The control of a single-entry rule-based inverted pendulum system was implemented with a fuzzy controller (Yi and Yubazaki, 2000). In another work, scientists have proposed energy-based and FLCs to control the inverted pendulum system (Muskinja and Tovornik, 2006). In another study, the authors applied the inverted pendulum system in the simulation environment by using the FLC for oscillation and stabilization (Ji et al., 1997). Elsayed et al. (2015) proposed sliding mode control and linear quadratic regulator control methods to balance an inverted pendulum system with a FLC and applied and compared them in an experimental and simulated environment. In another study performed, the fundamental performances of the FLC and the traditional PID controller were compared (Nour et al., 2007). According to the study, fuzzy control has been found to have smaller and shorter settlement times. Therefore, the advantage of fuzzy control draws attention. Roose and colleagues proposed a fuzzy parallel distributed compensation controller and implemented it in a simulated domain (Roose et al., 2017). Different studies have been done in the literature by using fuzzy logic method for controlling the inverted pendulum systems (Magana and Holzapfel, 1998; Oh et al., 2009; Wai and Chang, 2006).

### 2. Equations of motion of the mechanism

Newton–Euler method is used to obtain dynamic equations which have pivotal importance for use in robot control design algorithms (Walker and Orin, 1982). In Figure 2, free object diagram of an inverted pendulum system on a linearly moving car in the planar plane is demonstrated: the entire model, the car model and the inverted pendulum model.

The dynamic equations of the system are constructed using Newton’s second law of motion using the free body diagram of the system is given in Figure 2(b).

\[
\begin{align*}
    M\ddot{x}_\text{car} &= F + N - b\dot{x}_\text{car} \\
    M\ddot{\theta} &= F\cos\theta - b\dot{\theta}
\end{align*}
\]

where \(a_\text{car} (\ddot{x})\) and \(v_\text{car} (\dot{x})\) represent acceleration (\(\ddot{x}\)) and velocity (\(\dot{x}\)) of the car in the horizontal direction, respectively. After equation (1), in the FBD as shown Figure 2(c), the force \(N\) in the total of the forces in the horizontal direction is obtained as follows:

![Figure 1 Mechanical design representation of the inverted pendulum system](image-url)
The equations of motion of the system are obtained by the state space model. The state model, we are assuming the states to be as the cart position (\(x\)), cart linear velocity (\(\dot{x}\)), pendulum angle (\(\theta\)) and pendulum angular velocity (\(\dot{\theta}\)).

To obtain the state model, we are assuming the states to be as the cart position (\(x\)), cart linear velocity (\(\dot{x}\)), pendulum angle (\(\theta\)) and pendulum angular velocity (\(\dot{\theta}\)).

The equation of motion of an inverted pendulum mechanism on a moving car is created in the state space model; \(x = Ax + Bu\) form as follows:

\[
\begin{align*}
\dot{x} &= \frac{1}{\eta} \left( (I + mL^2)(F - b\dot{x}) + mL^2g\theta \right) \\
\dot{\theta} &= \frac{mL}{\eta} \left( (F - b\ddot{x}) + (M + m)g\theta \right)
\end{align*}
\]

The Taylor series is used to linearize nonlinear equations and to obtain a linear model, and the dynamic model of the system is obtained by the state space model. Table I shows the physical parameters of an inverted pendulum on a linearly moving car.

The equations of motion of the system are obtained by taking the following assumptions in the state space form as follows:

\[
\begin{align*}
\theta &= 0 \\
\sin\theta &= 0 \\
\cos\theta &= 1 \\
\dot{\theta}^2 &= 0
\end{align*}
\]

\[
\dot{\theta} = \frac{mL}{\eta} \left( (F - b\ddot{x}) + (M + m)g\theta \right)
\]

\[
\ddot{x} = \frac{1}{\eta} \left( (I + mL^2)(F - b\dot{x}) + mL^2g\theta \right)
\]

\[
\eta = MmL^2 + I(M + m)
\]

To obtain the state model, we are assuming the states to be as the cart position (\(x\)), cart linear velocity (\(\dot{x}\)), pendulum angle (\(\theta\)) and pendulum angular velocity (\(\dot{\theta}\)).

When equation (2) is substituted into equation (1), the second equation of motion is obtained:

\[
(M + m)\ddot{x} + b\dot{x} - mL\cos\theta \dot{x} + mL(\dot{\theta}^2)\sin\theta = F
\]

It is a well-known fact that the model with more complex equations is more accurate. It is always desirable to have a simple model because it is easy to understand. Therefore, a balance needs to be established between accuracy and simplicity.

### Table I Physical parameters of a linear inverted pendulum

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of car</td>
<td>M</td>
<td>2.4</td>
<td>kg</td>
</tr>
<tr>
<td>Mass of arm</td>
<td>m</td>
<td>0.23</td>
<td>kg</td>
</tr>
<tr>
<td>Moment of inertia of the arm</td>
<td>I</td>
<td>0.099</td>
<td>kg·m²</td>
</tr>
<tr>
<td>Length of arm</td>
<td>L</td>
<td>0.4</td>
<td>m</td>
</tr>
<tr>
<td>Car friction coefficient</td>
<td>b</td>
<td>0.05</td>
<td>N·s/m</td>
</tr>
<tr>
<td>Acceleration due to gravity</td>
<td>g</td>
<td>9.81</td>
<td>m/s²</td>
</tr>
</tbody>
</table>

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**Figure 2** Free body diagrams of (a) the entire model, (b) the car model and (c) the pendulum model of a linear inverted pendulum system.
3. Design of control algorithms applied to the system

When the controller is designed, it is aimed to keep the inverted pendulum on a linearly moving car in vertical angular stability and to bring the car to the equilibrium position. Real-time controls have been implemented on the real system by using the inverted pendulum system classical PID controller, FLC and self-tuning PID-type fuzzy adaptive controller designs. Although the PID control method is an old method used in many applications, it performs well (Ziegler and Nichols, 1942). In equation (14), the fundamental mathematical expression of PID method is seen (Ziegler and Nichols, 1993):

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{d}{dt} e(t)$$

In this study, the Ziegler–Nichols method, used by John G. Ziegler and Nathaniel B. Nichols, was applied for determining PID coefficients, and a closed loop control type was used in this method (Åström and Hägglund, 2001). Table II shows the control parameters obtained by the Ziegler–Nichols method. Each period of the system’s output oscillation is shown by $P_c$, and the highest gain of oscillation is shown by $K_c$.

Modeling, monitoring and real-time implementation of the inverted pendulum system was accomplished using the MATLAB package program and software of Feedback Company. Figure 3 shows the control systems of PID block diagram and fuzzy block diagram.

Table II Control parameters obtained by the Ziegler–Nichols method

<table>
<thead>
<tr>
<th>Control types</th>
<th>$K_p$</th>
<th>$K_i$</th>
<th>$K_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>$0.5 \times K_c$</td>
<td>$\infty$</td>
<td>0</td>
</tr>
<tr>
<td>$PI$</td>
<td>$0.4 \times K_c$</td>
<td>$0.8 \times P_c$</td>
<td>0</td>
</tr>
<tr>
<td>$PID$</td>
<td>$0.6 \times K_c$</td>
<td>$0.5 \times P_c$</td>
<td>$0.125 \times P_c$</td>
</tr>
</tbody>
</table>

PID-type fuzzy controller is a self-tuning automatic controller designed to set the coefficients of the PID control device and fuzzy control rules on-line. As it is known, these coefficients can be determined by complex mathematical operations and some formulations. In this respect, these determinations are often both difficult and can produce erroneous results. With adaptive control, the user is able to determine these coefficients more practically without the need for mathematical and formula operations by using their expertise and experience. The flow chart of the self-tuning PID type-fuzzy adaptive controller algorithm is shown in Figure 4.

The controller uses the errors and the rate of change of errors as input and adjusts the self-tuning parameters depending on the time-varying error ($e$) and the derivative of the error ($\dot{e}$). As the suggested self-tuning PID-type fuzzy adaptive controller aims to improve the control performance provided by a PID controller, it preserves the simple structure of the PID controller, and therefore, changing any hardware components of the original controller system becomes unnecessary for the application. Thus, the motivation of the developments on the system with adaptive control has been increased and its practicality has been ensured; $e$ and $\dot{e}$ are used the find the PID the three parameters ($K_p$, $K_i$ and $K_d$) with the fuzzy self-tuning method. In the operation, it constantly examines $e$ and $\dot{e}$, and then to achieve better dynamic performance, it ensures the controller by finding the optimum values of the three parameters with fuzzy control rules as adaptive on-line. In Figure 5, the block diagram is shown for self-tuning PID-type fuzzy controller.

Fuzzy logic uses approximate thinking instead of thinking based on exact values. In fuzzy logic, information is in the form of linguistic expressions (big, small, very few, etc.). Fuzzy inference process is performed by the rules defined between linguistic expressions. Fuzzy logic is very suitable for systems where the mathematical model is very difficult to obtain (Zadeh, 1988).
The rule base of an FLC is composed of a set of IF-THEN rules derived from the verbal expressions of expert persons who have knowledge about the system to be controlled (Soyguder et al., 2009; Soyguder and Ali, 2009). The rule base is considered the heart of an FLC, because all the other units and components are used to realize these rules in a reasonable and efficient way.

Here, it is aimed to keep the pendulum in balance during the minimum settlement period of the car while creating membership functions and rule table. In the selection of membership functions, other membership function types are tried, and the triangular type membership function, which is the most suitable membership function for this system, has been selected by us. Here, it is aimed to minimize the change of errors and errors according to time.

By using the classification in the rule table, appropriate operations are performed according to each input value, and the appropriate output is produced and the system is used more efficiently. For example, if the error is positive, the positive large output must be sent to the system to quickly bring this error to zero. If the error is negative, this value is applied to the input signal by applying a negative small signal and a more effective control is provided. The rule table for this system is given in Table III. It consists of 25 rules. Membership functions defined for the input values $e$ and $\dot{e}$ of the system are demonstrated in Figures 6 and 7. Membership functions defined for output value $\tau$ are shown in Figure 8.

In the control algorithms, $e$ – error – and $\dot{e}$ – the rate of change of error – constitute the system inputs. Here, error is the difference between the outputs of the system and the desired values. The output of the system is the appropriate torque value applied to the motors that drive the system to minimize error and the instantaneous change value of the error according to time. Here, the Mamdani method is used in adaptive fuzzy-PID and fuzzy logic type controls. The system control structure

**Table III** The rule table created for FLC

<table>
<thead>
<tr>
<th>$\tau$</th>
<th>NB</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>ZE</td>
<td>NB</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
</tr>
<tr>
<td>$\dot{e}$</td>
<td>PS</td>
<td>PB</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
</tr>
<tr>
<td></td>
<td>PB</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>
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consists of a total of two inputs and two outputs. These values are the position and angle information of the system. Here, we used the same rule table for all values. The rule table is defined in Table III. Here, the required control signals are produced in a way to minimize the error (e) and error change (d e) in the control (τ). Figure 9 shows input values and membership functions defined for e and d e. Tables IV–VI show the rule tables created for the Kp, Kd, and Ki values are shown, respectively. Figure 10 shows the membership functions defined for the output value of Kp, Kd, and Ki. The degree of each membership function is a value between 0 and 1, and triangular membership function has been used.

The values of the fuzzy control of the triangular membership functions used in Figures 6 and 7 were used the values between −60, −40, −20, 0, 20, 40, 60 and {−500, −300, −100, 0, 100, 300, 500}, respectively, for e and d e. The values in the range {−1, −0.8, −0.6, −0.4, −0.2, 0, 0.2, 0.4, 0.6, 0.8, 1} were used for the output value τ of the fuzzy control (Figure 8).

The fuzzy variables forming the rule tables shown in the above tables are created as follows: e, de, τ = { error, error change, control variable torque } {NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), PB (Positive Big)}. Input values of the FLC are specified in the {−60, 60} and {−500, 500} range. All input and output membership functions are taken as triangle-typed. The adaptive PID-type FLC system has two inputs (e, d e) and three outputs (Kp, Kd, Ki). The optimum values of the PID coefficients were determined by adapting adaptive fuzzy, and system control was ensured. The graphs of the triangular membership functions are shown in Figure 9. For the input values e and d e shown here, the values in the range of {−60, −40, −20, 0, 20, 40, 60} and {−500, −300, −100, 0, 100, 300, 500} were used respectively. At the same time, for Kp, Kd, and Ki which are the output values of the adapted control shown in Figure 10, values in the range of {0, 50, 100, 150, 200, 250, 300}, {0, 0.5, 1, 1.5, 2, 2.5, 3} and {0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50} were used, respectively.

The fuzzy variables forming the rule tables shown in the above table are created as follows: e, de = { error, error change, (NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), PS (Positive Medium), PB (Positive Big)).
PB (Positive Big), [-60, 60], [-500, 500], μ}, \(K_p, K_d, K_i\) = Control parameters, \(\{Z\text{ (Zero)}, PS\text{ (Positive Small)}, PM\text{ (Positive Medium)}, PB\text{ (Positive Big)}, [0, 1], \mu\}\). All membership functions are taken as triangle-typed for input and output.

4. Experimental results

In this section, experimental studies have been carried out on the inverted pendulum mechanism in the Robotics and Mechatronics Laboratory of Firat University using dynamic equations of the system. As known, inverted pendulum systems is one of the most basic real-time systems used in the determination of applicability and performance of designed control algorithms in engineering. The system is a two-degree of freedom and represents a type of inverse oscillation movement that is very common in real life. The performance values of the controller algorithms designed in this section are given graphically. Control variables of the system are position \(x\) and angle \(\theta\) parameters. The inverted pendulum system consists of a car placed on a rail and a pair of metal cranes mounted on either side of the center of the car. The bars can move freely in vertical position. The movement of the car is ensured by a belt connected to the DC motor. The right and left swinging and vertical balancing of the pendulum bars in the system is achieved by moving the car in which the pendulum is connected, to the right and left on the rail limited by the DC motor. The car has four wheels that will allow it to glide on the track. Figure 11 shows the mechanical installation of the system.

The movement of the car is mechanically restricted and in addition, there are limit switches which prevent movement when the car is passing toward the end of the rails for safety. The inverted pendulum system has optical encoders. The rotation speed of the shaft in the system varies depending on whether the signal period in the system is short or long. The encoders slow or accelerate the rotation speed of the shaft according to the incoming signal type. The rotation speed of the shaft can be determined from the encoder output. Figure 12 shows the control installation diagram of the inverted pendulum system.

The control unit required for the system can be designed in the MATLAB/SIMULINK package program and can be tested in a real-time experimentally appropriate manner, and the system can be controlled without the need for external processing via the PCI card. The PC is equipped with a data collection card which acts as an interface between the digital PC and the analog pendulum system. The digital control voltage generated from the PC via Matlab-Simulink® is converted to a \(\pm 5 \text{ V}\) analog value by the DAQ (data acquisition card) card, which is converted to \(\pm 24 \text{ V}\) by the DC motor interface for engine operation. The position of the car and the angle of the swing are measured with the help of two encoders. These encoders have an analog to digital converter that converts the analog values from the encoder to digital values and communicates with the DAQ board and PC. Figure 13 shows the flow diagram of the real-time operation of the inverted pendulum system.

We can list the steps used in the real-time work process as follows:

- In real-time study, the program analyzes the block diagram first and compiles it into rtw form.
- The Target Language Compiler (TLC) reads the file rtw and converts it into C code placed in the compilation directory in the MATLAB.
- TLC builds a target make-file and places it in the build directory.
- The program reads the created make-file and generates an executable file modeli.exe.

In this study, the control of the inverted pendulum system, which is located on a linear moving car, was performed through PID, fuzzy logic and self-tuning PID-type fuzzy logic control algorithms. The graphical results of the system were obtained using the MATLAB package program. By doing so, the best controller analysis was tried to be performed by obtaining the performance criteria of the control algorithms applied.

Experimental run times were determined to be 16 s. Experiments were carried out using a second-order derivative filter with a cut-off frequency of 100 rad/s and a damping ratio of 0.35. Figure 14 shows the images of the inverted pendulum experiment setup. Figure 15 shows the images obtained during the operation of the inverted pendulum experimental setup. Table VII gives the hardware list of the test setup.
Practically, the motors are known to have a voltage range or torque limit, in which the voltage range is ±2.5 V. So we used a saturation block to limit this range to ensure safety. The initial value of the car was $x = 0$ for all experiments. The angle of the pendulum was $\theta = 2\pi$ rad. The sampling time of the system is taken as 0.001.

Figure 13 Real-time flow diagram of the inverted pendulum system

Figure 14 Images of the inverted pendulum experimental setup in lab

Figures 16 and 17 show the arm angle ($\theta$) of the pendulum and the position of the car ($x$) obtained using the PID control method, respectively. Figure 16 shows that the arm angle of the pendulum reached the equilibrium position at 5.5 s and continued at an oscillation interval of $+0.20$ and $-0.20$. In Figure 17, it is seen that the car has reached equilibrium position after the 14th second, but continues between the $+0.07$ and $-0.04$ oscillation interval. Figures 18 and 19 show the arm angle of the pendulum obtained using the fuzzy control method and the position response of the car, respectively. In Figure 18, it was seen that the arm angle of the pendulum similarly reached the equilibrium position at 5 s, continuing at the oscillation interval of $+0.15$ and $-0.15$. In Figure 19, it is seen that the car has reached equilibrium position after the 14th second, but continues between the $+0.06$ and $-0.04$ oscillation interval. Similarly, Figures 20 and 21 show the arm angle of the pendulum obtained using the self-tuning PID-type fuzzy control method and the position response of the car, respectively. In Figure 20, it is seen that the arm angle of the pendulum reaches the equilibrium position at the 4.5th second. In Figure 21, it is seen that the car has reached equilibrium position after the 10th second, but continues between the $+0.03$ and $-0.03$ oscillation interval.

In Figures 22 and 23, the arm angle of the pendulum obtained using the self-tuning PID-type fuzzy logic control, fuzzy logic control and PID control methods and the position response of the car are shown. Various graphical performance criteria obtained by applying the designed control algorithms on real-time and real mechanism are compared. By comparing controllers, it was seen that the arm angle of the pendulum showed oscillation errors in response to the desired position.

In Figure 22, the fuzzy controller was found to have a lower amplitude and lower oscillation than the PID control method. The self-tuning PID-type fuzzy adaptive control method has the best result in the pendulum arm response, Followed by the fuzzy control and PID control methods.
Figure 15  Images obtained during the operation of the inverted pendulum experimental setup in lab

Table VII  Basic equipment of the inverted pendulum experimental set-up in laboratory

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC with PCI-1711 card</td>
<td>1</td>
</tr>
<tr>
<td>Pendulum Controller</td>
<td>1</td>
</tr>
<tr>
<td>Cable Adaptor of the system (SCSI)</td>
<td>1</td>
</tr>
<tr>
<td>Cart</td>
<td>1</td>
</tr>
<tr>
<td>Limit switches</td>
<td>2</td>
</tr>
<tr>
<td>DC Motor</td>
<td>1</td>
</tr>
<tr>
<td>The arms of the system</td>
<td>2</td>
</tr>
<tr>
<td>HCTL2016 IC</td>
<td>1</td>
</tr>
<tr>
<td>Connection cables and wires</td>
<td>2</td>
</tr>
<tr>
<td>Adjustable belt</td>
<td>1</td>
</tr>
<tr>
<td>Matlab, Simulink, Real-Time Workshop, Advantech PCI-1711 device driver, Feedback Pendulum Software</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 16 Response of pendulum’s arm angle obtained by the PID control method

Figure 17 Response of cart position obtained through the PID control method

Figure 18 Response of pendulum’s arm angle obtained by the fuzzy control method

Figure 19 Response of cart position obtained through the fuzzy control method

Figure 20 Response of pendulum’s arm angle obtained through the self-tuning PID-type fuzzy adaptive control method

Figure 21 Response of pendulum’s arm angle obtained through the self-tuning PID-type fuzzy adaptive control method

Figure 22 The angle variation for pendulum when the PID, fuzzy logic and the self-tuning PID-type fuzzy adaptive controllers are implemented

Figure 23 The position variation of cart when the PID, fuzzy logic and the self-tuning PID-type fuzzy adaptive controllers are implemented
The PID controller showed the worst performance in terms of reaching the pendulum’s arm to the equilibrium position. Figure 23 shows the variations of the applied control methods for the position of the vehicle. In this way, the time response of the position of the car is clearly seen. In the response positions compared, it has been seen that PID control method has a larger overshoot amplitude. It has been observed that the overshoot amplitude in the fuzzy control method is lower than the PID control method and gives less oscillation error. The reason for the increase in error in the fuzzy control is the rough and nature of its membership function.

PID controller showed the worst performance in reaching the car to the equilibrium position. As a result of the analysis of the settlement time in the response of the position of the car, it is seen that the self-tuning PID-type fuzzy adaptive control method has the lowest amplitude for this system among others and is more applicable among the methods. It should be noted that the basic goal of the adaptive control is to improve the performance of the system with the rule tables to be created by a better user and a better expert about the system.

As a result, the self-tuning PID-type fuzzy adaptive control method has the lowest settling time ($t_s$). While the arm angle of the pendulum controlled by PID and fuzzy control methods had almost the same settling time, the self-tuning PID-type fuzzy adaptive control method showed the best performances with lower amplitude and earlier settling time in the equilibrium of the car. Among the methods, it was seen that self-tuning PID-type fuzzy adaptive control method is applicable for inverse pendulum systems.

5. Conclusion

In this study, the equations of the motion an inverted pendulum system on a linear moving car have been obtained, and the system control has been performed by applying the classical PID, fuzzy logic and self-tuning PID-type fuzzy adaptive controller algorithms designed on the inverted pendulum mechanism in Robotics and Mechatronics Laboratory of Firat University in real-time. With the proposed controller algorithms, the aim is to keep the pendulum in vertical angular stability and to bring the linear moving vehicle to the equilibrium position. Optimum values of the PID coefficients ($K_p$, $K_i$, $K_d$) are adaptively optimized in the self-tuning PID-type fuzzy adaptive controller design. The designed controllers are implemented on a real-time and real system and compared with the graphical results of the system’s performance results. As a result, the self-tuning PID-type fuzzy adaptive control method, among the designed controllers, has the lowest amplitude in reaching the stability position of the car and has the best performance compared to the others during the minimum settling time.

References


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