Performance Enhancement of Sliding Mode Control Using Fuzzy Logic: An Application And Analysis

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Abstract: Sliding mode control (SMC) is an efficient tool in design of robust controller for nonlinear plants. The main advantage of sliding mode control is order reduction and making the system practically independent of variation in plant parameter. With faster switching circuits sliding mode control is proving to be a great tool. The inherent problem of sliding mode control is chattering. Out of the numerous possibilities fuzzy logic controllers are the best option. Many researches have been done in this field. This paper presents the application of SMC. An inverted pendulum system and a physical world problem of underwater vehicle are presented for analysis. The problem of chattering is then addressed. Fuzzy logic is next applied to improve the performance obtained by SMC.

Keywords: Sliding mode control, fuzzy logic control, chattering, inverted pendulum, underwater vehicle.

I. INTRODUCTION

The sliding mode control approach started nearly half a decade ago in Soviet Union [1]. With the current development in semiconductor technology fast switching circuits are being developed. This paves way for sliding mode control to take over from conventional control techniques especially in case of high order nonlinear systems. The major advantage of SMC is low sensitivity to plant parameter variation. Sliding mode Control implies the control is discontinuous state function which may be easily implemented by controllers using simple on/off control. Hence sliding mode control finds ample use in robotics, process control, plant automation, electric drives, vehicle motion control. The major problem associated with the SMC is of high frequency disturbance referred to as chattering. Fuzzy logic controller removes the problem of chattering appearing in the sliding mode controllers.

II. BASICS OF SMC

Sliding Mode Control, often referred to as Variable Structure Control, is a high-speed switching feedback control that switches between two values based upon some rule [2],[3]. The control theory uses a high-speed switching control law to drive the nonlinear plant’s state trajectory onto a specified surface in the state space. This surface is called the sliding or switching surface. [4]. Consider a system with state space equation given as

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= -\psi x_1
\end{align*}
\]

(1)

Let \(\psi = 5\). Then

\[
\begin{align*}
\frac{dx_1}{dx_2} &= -\frac{x_2}{5x_1} \\
5x_1\frac{dx_1}{dx_2} + x_2 \frac{dx_2}{dx_2} &= 0 \\
\frac{5x_1^2}{2} + \frac{x_2^2}{2} &= R^2
\end{align*}
\]

(2)

(3)

(4)

Let \(\psi = 0.2\). Then

\[
0.2\frac{x_1^2}{2} + \frac{x_2^2}{2} = \text{constant}
\]

\[
\psi = \begin{cases} 
5 & \text{if } x_1x_2 > 0 \\
0.2 & \text{if } x_1x_2 < 0 
\end{cases}
\]
The equations illustrate a variable structure system, as the system takes on different structures with changing values of constant. The final equation illustrates spiraling around origin. Sliding mode control is essentially variable structure control along the given surface. Switching function is chosen from system trajectories. In general, the switching function is chosen using the system trajectories. These are known as sliding modes. [5].

Consider the double integrator \( \ddot{x} = u \) with state space model given by:

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= u
\end{align*}
\]  
(6)

(7)

Let \( u = +2 \). The two independent structures are as shown in Fig 1. Both of these are unstable. With the implementation of switching logic \( u = -2 \sign(x_1 + x_2) \), [6], the closed-loop system changes its structure anytime the state trajectory crosses the line \( x_1 + x_2 = 0 \). As shown in Fig 2.

\[
x_1 + x_2 = 0. \text{ As shown in Fig 2.}
\]

III. ORDER REDUCTION

Consider a general nth order system given by:

\[
\begin{bmatrix}
0 & 1 & 0 & \cdots & 0 \\
0 & 0 & 1 & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & \cdots & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
\vdots \\
x_n - 1 \\
x_n
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
\vdots \\
0 \\
1
\end{bmatrix}
\begin{bmatrix}
u
\end{bmatrix}
\]

(8)

Let the sliding surface be:

\[
S(x) = sx
\]

(9)

\[
= \left[ s_1, s_2, \ldots, s_n - 1 \right]
\]

(10)

The new state space equation shows the reduced order of system from n to n-1.

IV. FUZZY LOGIC CONTROLLER

A lot of literature is available on fuzzy logic controller and their application to various fields. The basics of fuzzy logic are illustrated clearly in Fig3. Fuzzy logic can model the nonlinear relationship between inputs and outputs. It can simulate the operator’s behavior without use of mathematical model. It is a method that transfers human knowledge into mathematics, with the aid of if–then rules [7].
As an example to demonstrate the effectiveness of fuzzy logic controllers the fuzzy based temperature controller in a shower is studied. The temperature and flow rate are fed to the fuzzy logic controller as input. The Controller designed in MATA LB using Fuzzy logic Controller toolbox as shown in Fig 4-6.

The membership functions of temperature and flow are shown in Fig 5 and Fig 6.

Using the desired if and rule base the Fuzzy logic controller is designed. This controller can then be used to control temperature and flow rate in shower. The Simulink model is shown in Fig7. The hot and cool temperature can be set as per the requirement.

V. INVERTED PENDULUM

The inverted pendulum problem is one of the most studied problems in control engineering. The system consists of cart and pendulum attached to it as shown in Fig 8.
The aim of the controller is to apply the right amount of force to stabilize the pendulum in the upright position. An intuitive way of swinging the pendulum to the upright position is to consider the energy stored in the system and comparing it to the value which corresponds to the maximum height. [8]. The control law approach is similar to SMC.

The model is best described by nonlinear differential equations

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

\[m \ddot{x} \cos(\theta) + ml \ddot{\theta} = mg \sin(\theta)\]  

The state space model is given as:

\[
\begin{bmatrix}
    \dot{\theta} \\
    \dot{x} \\
    \dot{\dot{x}} \\
    \ddot{\theta}
\end{bmatrix} =
\begin{bmatrix}
    g1(\theta, \dot{\theta}, x, \dot{x}, u) \\
    g2(\theta, \dot{\theta}, x, \dot{x}, u)
\end{bmatrix}
\]

The values of parameters \(g1\) and \(g2\) are:

\[g1 = \frac{(M + m)g \sin \theta + b \cos \theta \dot{x} - ml \sin \theta \cos \theta \dot{\theta}^2 - \cos \theta u}{l(M + m \sin^2 \theta)}\]

\[g2 = \frac{-mg \sin \theta \cos \theta - bx + ml \sin \theta \dot{\theta}^2 + u}{M + m \sin^2 \theta}\]

To apply SMC approach let,

\[X2 = -ax1\]  

As 

\[X1 = X2\]  

So 

\[X1 = -ax1\]

Let the surface be

\[S = aX1 + X2\]

The Lyapunov function:

\[V = \frac{1}{2} S^2\]

\[\dot{V} = S \dot{S} = S (a\dot{\theta} + \frac{\dot{a}}{\dot{\theta}} \dot{\theta})\]

From Lyapunov theory follows that the sliding surface will be reached as long as the derivative of \(V\) remains negative definite. This leads to the control law

\[u = \frac{1}{g(x)} (-a\dot{\theta} - f(x)) - k \text{sign}(S)\]

The control law depends on the sign of \(S\), thus effectively realizing SMC. \(g(x)\) and \(f(x)\) are functions of \(\theta\) and the parameters of system which can be easily derived from the above set of equations. The above system of equation is used to get the SIMULINK model for SMC of inverted pendulum system. The results obtained are plotted in figure 9-12.
It has to be noted that a switching control law where the sign of the control input depends on the system states value in comparison to the sliding surface “chattering” can occur. It is because the control law always strives for the system being driven towards the sliding surface. However, as it will never reach the surface exactly but rather always end up on the opposite side the control input will rapidly switch for system states close to the surface[9]. It is clear from figure 11 that the SMC brings the pendulum angle back to the desired state within a very short time. From figure 12 it is clear that the input force is not smooth but consists of some disturbance. This is called chattering.

This problem of chattering can be removed by various techniques. Fuzzy logic Controllers is described as the best techniques to remove the chattering problem. As shown by Shiuh-Jer Huang, Hung-Yi Chen and Chen-Chuan Wang in their paper for temperature controller [10], the chattering problem is overcome by applying the fuzzy based approach. Jan stellet also discusses the application of FLC to remove the problem of chattering appearing in the control of inverted pendulum, when SMC is applied. FLC can be easily applied to above problem of Inverted problem and make the control chattering free.

VI. Underwater Vehicle

To compare the results of SMC and fuzzy SMC both control techniques are applied to a physical world problem of underwater vehicle. The model of underwater vehicle is first drawn in SIMULINK and then the SMC is applied to control the underwater vehicle. The model is shown in figure 13.

It is clear from the figure that the aim of the controller is to make the system track the reference signal. A sinusoidal signal is used here as the reference signal. The problem with the conventional sliding mode controller is that the chattering occurring in the input signal deteriorates the tracking performance. To improve the performance of the SMC and thus achieve a better controller fuzzy logic is applied. The application of fuzzy logic removes the chattering occurring in the input force of the sliding mode controller. The combined controller consists of fuzzy logic in cascade with sliding mode controller. The comparative analysis of the control input is shown in figure 14. The blue plot is of conventional SMC and the red plot is of fuzzy SMC. It is clear from the figure that the FSMC shows less chattering compared to the conventional SMC. Visually chattering is seen as spikes in the figure. It is also observed that there is still some chattering left in the control input after applying fuzzy logic. This is due to somewhat inferior rule base. With proper rule base suited for the application chattering free plot is observed as shown by green plot of figure 14.

VII. CONCLUSION

The advantages of fast switching circuits are taken by the advancements in control circuits. SMC
helps in smooth control of a higher order nonlinear system. The advantages of order reduction and insensitivity to parameter variation are illustrated. The most prominent problem of SMC is chattering which can be overcome by integrating the SMC with Fuzzy logic controllers. The rule base of fuzzy logic must be properly designed. An ill designed rule base may deteriorate the performance of the controller. With proper rule base fuzzy logic can significantly improve the performance off SMC. Thus making an advanced control circuitry for application in robotics, process control, plant automation and other areas of control engineering.

REFERENCES

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