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Proposal of Sliding Mode Controller based on Backstepping Technique for Control of Magnetic Levitation System

Arobindra Saikia, Neelanjana Baruah

Abstract: *Magnetic Levitation System (MLS) is a nonlinear system and it is used extensively in many areas. The system's goal is to use the non-contact principle to magnetize the coil and cause the objects to float to a specific height. The magnetic force and the current flowing through the coil have a nonlinear relationship. In this paper first design of the backstepping controller is done to attain the wanted floating in presence of system related uncertainties and system behavior is witnessed. Then a Sliding Mode Controller (SMC) based on backstepping procedure is formulated. The control gains in this controller are designed in such a way that the characteristics polynomial whose coefficients are control gains is strictly Hurwitz and the closed loop system's asymptotic stability is assured. Simulations are performed and the magnetic ball tracking is observed considering step signal as reference in presence of disturbances. More accuracy is observed in terms of following the reference by the magnetic ball when it is used Sliding Mode Controller based on Backstepping technique instead of backstepping controller by considering pulse type disturbance. By simulation and analyzing results it is confirmed that the proposed control strategy is more effective.*

Keywords: *backstepping, disturbance, magnetic levitation, PID.*

I. INTRODUCTION

Sliding Mode Controller (SMC) is a robust controller and it can perform exceptional tracking in presence of uncertainties and external disturbances. SMC is used extensively in many applications such as (a) Petrochemical systems for various processes control [1], (b) Servomotor position and speed control system [2], (c) Aerospace applications-the altitude control of spacecraft [3], (d) Automobile systems-the antilock braking control [4] (e) Robotics systems[5] (f) Mechanical systems [6]. The backstepping controller alone cannot provide the robustness to the uncertainty and disturbances to the present in the systems. Hence backstepping based SMC [7] is suggested formulated and realized for Magnetic Levitation System (MLS) and it behaves in a severely nonlinear manner. SMC based on Backstepping technique astonishes researchers by allowing them to control the ball's position in MLS while dealing with modeling and parametric uncertainties.

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***** Correspondence Author

Arobindra Saikia*, Department of Instrumentation Engineering, Jorhat Engineering College, Jorhat, India. Email: arvind_saikia@yahoo.com

Neelanjana Baruah, Department of Instrumentation Engineering, Jorhat Engineering College, Jorhat, India. Email: neelanjana.bb@gmail.com

The performance enhancement of the proposed controller can be achieved by selecting suitable sliding surface and designing the control law. The gravitational force drags an object downward, whereas the electromagnetic force holds it in the air. It is referred to as a magnetic levitation system in general (Maglev System). Because the MLS has no mechanical contacts, so friction, wear, or other mechanical issues are absent. Magnetic levitation systems have a wide range of applications, including magnetic frictionless bearings in spaceships, vibration separation of sensitive machinery in enterprises, and molten metal levitation in induction furnaces. The maglev system is a very intriguing test field from the perspective of control theory since its nature is nonlinear and contains unbalanced nonstop balance points, as well as it is widely used in industry. Many control techniques have been realized for Maglev System. For position control feedback linearization methodology is used in [8] where tracking of sine wave is obtained; however it shows poor results when other signals are used as reference.

The quantitative feedback theory [9] is researched, although just a few tests were recorded. In [10], a partial state feedback controller was presented, however parameter uncertainties were not included in the noise attenuation analysis.

SMC provides good tracking performance and some of the SMC based works is described here. In [11] classical controllers and SMC are compared experimentally and it is ascertained that SMC is advantageous but disturbance rejection could not observed. PI-SMC is used in [12] where sine wave and square wave tracking shows that 0.07s time lag exists. SMC based on DSP is considered for MLS [13] in which different SMC methods are compared namely conventional SMC, Adaptive SMC design approaches based on lumped uncertainty estimators and terminal SMC design methodologies based on exact estimators, and the design was bit complex. [7] proposed discrete backstepping control of a MLS using a nonlinear state estimator, which yielded promising results.. Backstepping Based Nonlinear Adaptive Control of Magnetic Levitation System with Unknown Disturbances was suggested in [14], and it successfully rejected disturbances. Adaptive SMC based Backstepping controller for a Co-Ordinated Links (COOL) Robotic Arm was proposed in [19]. According to the above-mentioned literature, SMC controllers are only designed for rejecting disturbance and also for servo tracking or tracking square wave with time lag. Again backstepping controllers are also designed to control MLS in presence of disturbances.

In this paper the author proposes to combine both backstepping and SMC so that more accurate and precise control of MLS is achieved although disturbances and uncertainties may influence. The following is how this paper is organized: The first section is the same as the last one. Section II describes the mathematical modeling of a magnetic levitation system more clearly. The back stepping controller and back stepping based sliding mode controller designs are explained in Section III. The simulation and actual findings for different tests are visually presented in Section IV. In Section V, the system and controllers are discussed and conclusions are drawn.

II. MATHEMATICAL MODELLING OF THE SYSTEM

Fig. 1 shows schematically the figure of magnetic levitation system.

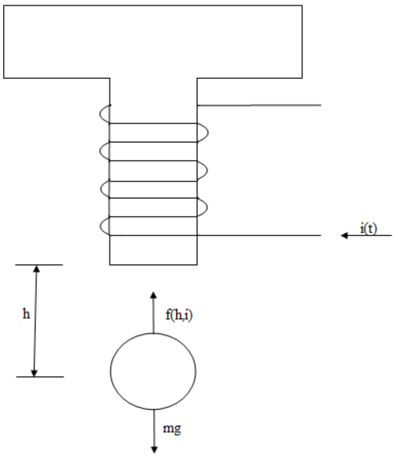

Fig. 1. Magnetic levitation system [18]

Newton's Law of Motion is used to derive the dynamic equation for a ball which is influenced by gravity is:

$$m\ddot{h} = mg - f(h,i) \tag{1}$$

In this equation the ball mass is denoted by m, g is the acceleration due to gravity and the magnetic force is denoted by *f(h,i)*. A force is developed due to magnetic effect and can be written as,

$$f(h,i) = \frac{i^2}{2} L_0 h_0 \frac{1}{h^2} \tag{2}$$

Here current flowing through the coil is denoted by i, the increment in inductance due to ball is denoted by L_0 and furthermore the levitating ball position in equilibrium is denoted by h_0 respectively. Constant k_0 is used to denote$\frac{L_0 h_0}{2}$.

So the final equation can be written as

$$m\ddot{h} = mg - k_0 \frac{i^2}{h^2} \tag{3}$$

Now considering h=x_1 , $\dot{h} = x_2$ and $\frac{k_0}{m}$ is denoted by another constant *P*. Furthermore position and velocity of the ball are denoted byx_1,x_2 respectively.

Expressing the system in state space form in the following way,

$$\dot{x}_1 = x_2 \tag{4}$$

$$\dot{x}_2 = g - P\frac{i^2}{x^2} \tag{5}$$

III. FORMULATION OF BACKSTEPPING CONTROLLER

Backstepping control [7] is defined as a recursive approach to control system. The system is separated into two sub-systems in this study. For the first sub-system, a virtual control is examined, and the first sub-system is stabilized using the Lyapunov stability theorem. The second sub-system is then stabilized utilizing virtual control of the first sub-system and the Lyapunov stability theorem, and a final control law is derived, which controls the entire system. The procedure for formulation is splitted into the following steps.

Step 1: Using error z_1 as $z_1 = x_1 - x_r$ here x_r is considered as reference position of the levitated ball. Following Lyapunov function is used for step 1

$$V_1 = \frac{1}{2} {z_1}^2 \tag{6}$$

Differentiating (6) we get

$$\dot{V}_1 = z_1 \dot{z}_1 \tag{7}$$

The time derivative of z_1 is,

$$\dot{z}_1 = \dot{x}_1 - \dot{x}_r$$

$$\dot{z}_1 = x_2 - \dot{x}_r \tag{8}$$

If $\dot{z}_1$=-$c_1 z_1$, then $\dot{V}_1$ becomes negative definite and only stability of the sub-system 1 will be confirmed. A virtual control α_1 is defined as $-c_1 z_1$, and furthermore c_1 is always positive.

Step 2: Defining a new error z_2 as,

$$z_2 = x_2 - \alpha_1 \tag{9}$$

$$\dot{z}_2 = \dot{x}_2 - \dot{\alpha}_1$$

$$\dot{z}_2 = g - P\frac{u}{{x_1}^2} + c_1 \dot{z}_1 \tag{10}$$

Following Lyapunov function is used for sub-system 2

$$V_2 = \frac{1}{2} {z_2}^2 \tag{11}$$

The time derivative of V_2 becomes

$$\dot{V}_2 = z_2 \dot{z}_2 \tag{12}$$

Subsystem 2 to be stable if $\dot{V}_2$ is negative definite. In order to satisfy that condition $\dot{z}_2$ is to be equal to$-c_2 z_2$, and here c_2 must be a positive constant. Hence it is,

$$-c_2 z_2 = g - P\frac{u}{{x_1}^2} + c_1 \dot{z}_1 \tag{13}$$

But from (8), $\dot{z}_1 = x_2 - \dot{x}_r$,

Using (13) the required control law is found as,

$$u = \frac{{x_1}^2}{P}\{c_2 z_2 + g + c_1(x_2 - \dot{x}_r)\} \tag{14}$$

IV. SLIDING MODE CONTROLLER DESIGN BASED ON BACKSTEPPING TECHNIQUE

The following PID (Proportional-Integral-Derivative) sliding surface is used to design the required controller,

$$s = (c_1 + c_2) z_1 + c_1 c_2 \int_0^t z_1 dt + \dot{z}_1 \tag{15}$$

Therefore, the sliding surface of the PID is obtained based on the backstepping procedure [19], where calculation of each constant is done based on how each subsystem can be made stable and therefore additionally there is no need of extra tuning method for the surface parameters. Sliding surface s is used to represent error variablez_2.

Hence,

$$\dot{s} = \dot{z}_2$$

$$\dot{s} = \dot{x}_2 - \dot{\alpha}_1$$

$$= g - P\frac{u}{x^2} + c_1\dot{z}_1 \quad (16)$$

So, following Lyapunov function is taken for the second sub-system as

$$V_3 = \frac{1}{2}s^2 \quad (17)$$

Differentiating (17) we get

$$\dot{V}_3 = s\dot{s} \quad (18)$$

Since $\dot{V}_3$ has to be negative definite in order to make this subsystem stable so $\dot{s}$ is taken as –ksign(s)-ws and k is a positive constant. So the control law can be obtained as

$$u = \frac{{x_1}^2}{P}\{g + c_1\dot{z}_1 + k\mathrm{sign}(s) + ws\} \quad (19)$$

V. RESULTS AND DISCUSSION

The proposed controller's simulation was carried out in MATLAB/Simulink. Figures 3 and 4 illustrate the results of simulation of both the backstepping controller and the backstepping-based SMC. As a reference a step signal is used. The magnetic ball's tracking performance with respect to the reference signal, tracking error, and system states, which are the ball's velocity and position, are all obtained. A pulse signal is used as disturbance to the system, and magnitude of pulse is of unit magnitude and time interval of applied pulse is of 5 seconds and stabilization of the system is done by using both controllers even if there are disturbances. The values of different parameters of the system under consideration [14] are as follows

TABLE 1. PARAMETERS OF MAGNETIC LEVITATION SYSTEM [14]

SYMBOL	VALUES	UNITS
m	20×10^{-3}	kg
L_0	5.518125×10^{-3}	H
h_0	0.009	m
A	$1.241578125 \times 10^{-3}$	mH/kg
g	9.81	m/s^2

Setting the tuning parameters manually as $c_1 = 5$, $c_2 = 8$, k = 20 and w = 5 and carrying out the simulations in presence of disturbance. Figure 2 shows the results of simulation of tracking the operation of the backstepping controller. Fig. 3 shows the system states. The tracking performance of SMC based on backstepping procedure is shown in Fig. 4. System's states variables are shown in Fig. 5

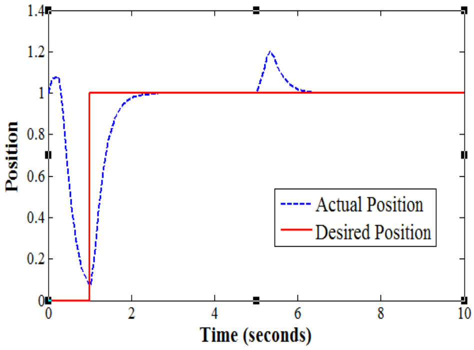

Fig. 2. Position response of backstepping

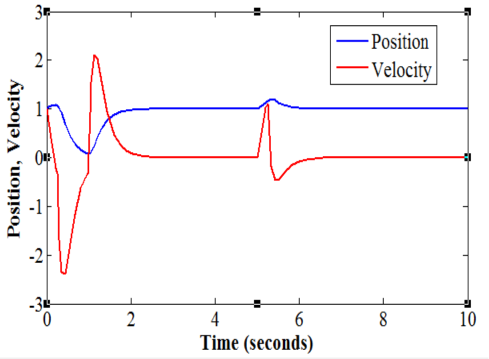

Fig. 3. State variables x_1, x_2 plots

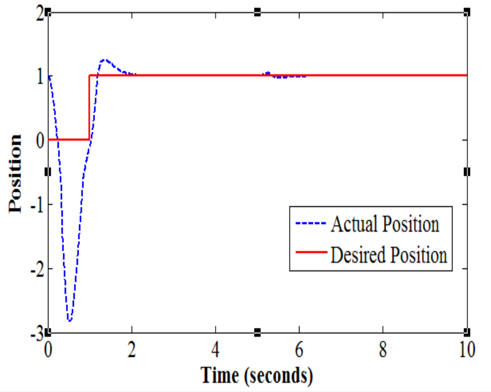

Fig.4. Position response of backstepping based SMC

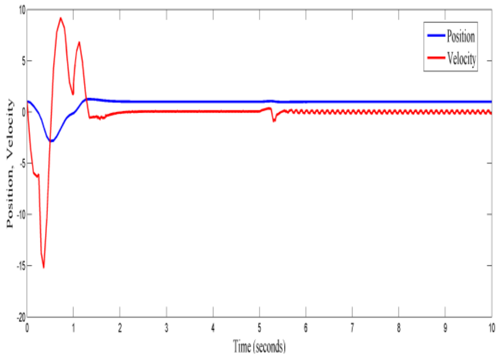

Fig. 5. State variablesx_1, x_2 plots

VI. CONCLUSION

A sliding mode controller based on backstepping technique is formulated for a magnetic levitation system in this study. Initially, a backstepping controller is created, and then determination of the velocity, position of the magnetically levitated ball is done and also determination of tracking of the magnetically levitated ball is obtained. Finally, a backstepping based SMC is created utilizing a PID sliding surface. Even in the presence of disturbance, the backstepping-based sliding mode controller regulates the states and hunts down the levitated ball more quickly with fast response. So the stability of Magnetic levitation system is improved by using SMC based on backstepping technique.

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AUTHORS PROFILE

Mr. Arobindra Saikia, Assistant Professor. Instrumentation Engineering Department, Jorhat Engineering College, Jorhat, Assam, India, arvind_saikia@yahoo.co.in BE: Instrumentation Engineering, Jorhat Engineering College, Dibrugarh University. M Tech: Electronic Design & Technology, Tezpur Central University Research Interests: Instrumentation and Control, Nonlinear Control, Intelligent control.

Dr. Neelanjana Baruah, Professor, Department of Instrumentation Engineering, Jorhat Engineering College, Jorhat received B.E degree in EE from Assam Engineering College affiliated to Guwahati University, Guwahati, Assam. M. Tech Degree in Instrumentation Engineering from IIT Kharagpur. After this she completed her Ph.D. in Power System Stability from Guwahati University, Assam. Her research interests include Instrumentation and Power System stability.