Brief Paper

Adaptive robust nonlinear control of a magnetic levitation system

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Abstract

This paper proposes an adaptive robust nonlinear controller for position tracking problem of a magnetic levitation system, which is governed by an SISO second-order nonlinear differential equation. The controller is designed in a backstepping manner based on the nonlinear system model in the presence of parameter uncertainties. At the first step, a PI controller is designed to stabilize the position error of the levitated object. Then at the second step, an adaptive robust nonlinear controller composed of an adaptive feedback linearization control term and a robust nonlinear damping term is designed, to attenuate the effects of parameter uncertainties. The combined adaptive and robust approach helps to overcome some well-known practical problems such as high-gain feedback of the robust controller, and poor transient performance of the adaptive controller, so that better control performance can be achieved compared to the case where either is employed alone. Experimental results are included to show the excellent position tracking performance of the designed control system. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Magnetic levitation systems are widely used in various fields such as frictionless bearings, high-speed maglev passenger trains, levitation of wind tunnel models, vibration isolation of sensitive machinery, levitation of molten metal in induction furnaces, and levitation of metal slabs during manufacture (Barie & Chiasson, 1996). It is an important task to construct a high performance feedback controller to control the position of the levitated object since a magnetic levitation system is usually strongly nonlinear and open-loop unstable. Recently, a lot of works have been reported in the literature, for controlling a magnetic levitation system by actively taking the nonlinearities of the system model into account (Cho, Kato, & Silman, 1993; Lu & Chen, 1994; Barie & Chiasson, 1996; Charara, Miras, & Caron, 1996; Trumpeter, Olson, & Subrahmanyan, 1997; Yeh & Youcef-Toumi, 1998; Annaswamy, Thanomsat, Mehta, & Loh, 1998; Green & Craig, 1998).

High performance control of a magnetic levitation system of attractive type in the presence of parameter uncertainties is of particular interest. To achieve robustness of the control system, sliding-mode control techniques have been mostly applied (Cho et al., 1993; Charara et al., 1996). This approach however, may result in large control efforts and chattering control response. There have been only few experimental results on adaptive control of magnetic systems reported in the literature, mainly due to the poor transient performance of an adaptive controller. Adaptive controllers based on nonlinear parametrization (Annaswamy et al., 1998), local function estimation (Yeh & Youcef-Toumi, 1998) and backstepping design approach (Green & Craig, 1998), respectively, have been reported most recently. However, the algorithms and stability analyses of the first two seem quite complicated, and no attention is paid to the transient performance in all the three works. Additionally, it can be found in Green and Craig (1998) that the results exhibit large overshoots. In Lu and Chen (1994), an adaptive fuzzy controller is employed to avoid large control efforts of the robust sliding-mode controller. This method which incorporates both adaptive and robust mechanisms, requires a large number of multi-input
fuzzy rules and hence the control algorithm becomes quite complicated.

In recent years, the backstepping control design techniques have received great attention due to its flexibility for systematic desirable modifications of the controller such as compensation for modelling errors or external disturbances (Krstic, Kanellakopoulos, & Kokotovic, 1995). Robust control techniques account for fast time variations of modelling errors or external disturbances, but usually require high feedback gain to achieve a small tracking error. On the other hand, adaptive control techniques only account for constant uncertain parameters and external disturbances via parameter adaption, but they can ensure a small tracking error after the transient phase without requiring a high feedback gain. A combined use of these two control techniques may help to overcome some well-known practical problems of either the robust controller or the adaptive controller. Along this line, developments of adaptive versions of robust nonlinear control designs have been reported in last years (Yao & Tomizuka, 1997; Freeman, Krstic, & Kokotovic, 1998).

Motivated by these considerations, this paper proposes an adaptive robust nonlinear controller for a magnetic levitation system with current feedback power amplifier, via the backstepping design approach. At the first step, a PI controller is designed to stabilize the position error of the levitated object. Then at the second step, an adaptive robust nonlinear controller is designed to attenuate the effects of parameter uncertainties as possible, so that a small velocity error is ensured. The velocity controller designed at the second step is composed of two parts, i.e., an adaptive feedback linearization control term, and a robust nonlinear damping term (Krstic et al., 1995; Krstic, Sun, & Kokotovic, 1996). Stability and transient performance of the designed control system are analyzed, and experimental results are included to show the excellent position tracking performance of the designed control system.

2. Model of the magnetic levitation system

Consider the magnetic levitation system shown in Fig. 1. This is a popular gravity-based one degree-of-freedom magnetic levitation system, in which an electromagnet exerts attractive force to levitate a steel ball (in some references a steel plate is levitated). If the coil current is controlled by a current feedback power amplifier as in most applications, then the system dynamics can be described in the following equations (Cho et al., 1993; Lu & Chen, 1995; Trumper et al., 1997; Green & Craig, 1998):

\[ \begin{align*}
\dot{x}_1 &= x_2, \\
\dot{x}_2 &= g + \phi(x_1) x_2^2.
\end{align*} \]  

(1)

\[ \phi(x_1) = -\frac{Q}{2M(x_x + x_1)^2}, \]  

(2)

where \( x_1 \) is the air gap (vertical position) of the steel ball, \( x_2 \) the velocity of the steel ball, \( i \) the coil current, \( g \) the gravity acceleration, \( M \) the mass of the steel ball, and \( Q \) and \( x_x \) are positive constants determined by the characteristics of the coil, magnetic core and steel ball.

In practice, it is impossible to know the nonlinear function \( \phi(x_1) \) completely due to parameter uncertainties, we therefore approximate the nonlinear function \( \phi(x_1) \) by a radial basis function (RBF) network which is linear-in-the-parameters, as the following (Poggio & Girosi, 1990):

\[ \tilde{\phi}(x_1, \omega) = \sum_{n=1}^{N} w_n r(x_1 - p_n), \]  

(3)

where \( \omega = [w_1, w_2, \ldots, w_N]^T \) is the vector composed of the weight parameters of the network, and

\[ r(x_1 - p_n) = \exp \left[ -\frac{1}{2} \left( \frac{x_1 - p_n}{\sigma} \right)^2 \right] \]  

(4)

is a Gaussian basis function, in which \( p_n \) denotes the center of the \( n \)th basis function, and \( \sigma \) determines the width of the basis functions. In this study, the basis functions are equidistantly located in \( X = \{ x_1 | 0 \leq x_1 \leq x_{1M} \} \subset \mathbb{R} \), i.e., the physically allowable operating region of \( x_1 \) (see Fig. 1). When the distance \( D \) between two adjacent centers is determined, \( \sigma \) can be determined as follows (Yang et al., 1994):

\[ \sigma = \sqrt{\frac{2}{\pi}} D \approx 0.45D. \]  

(5)

Before providing the design procedure of the adaptive robust nonlinear controller, some assumptions are made here.

Fig. 1. Diagram of the magnetic levitation system.
Assumption 1. A sufficient number of basis functions are included into the RBF network, so that the network can approximate \( \phi(x_1) \) within a sufficient accuracy, i.e., there exists a desired \( \hat{w}^* \) such that
\[
|\phi(x_1) - \hat{\phi}(x_1, \hat{w}^*)| \leq \varepsilon, \quad x_1 \in X,
\]
where \( \varepsilon \) is a sufficiently small positive real number.

It should be mentioned here that even when the value of \( \varepsilon \) is not very small, the stability of the closed-loop system can still be guaranteed in virtue of the robust control term introduced later. Of course, sufficient accuracy may lead to a small ultimate control error, as shown later in Lemma 1.

Assumption 2. The lower and upper bounds of the weight parameter vector \( w \) and the gravity acceleration \( g \) are known a priori, i.e.,
\[
w \leq w \leq \bar{w} < 0, \quad 0 < g \leq g \leq \bar{g}.
\]

Notice that an external constant (or slowly varying) disturbance can also be included into \( g \) equivalently, i.e., the gravity acceleration is biased equivalently.

Assumption 3. The nominal nonlinear function is known a priori, i.e.,
\[
\phi_0(x_1) = -\frac{Q_0}{2M_0(x_{x,0} + x_1)^2}, \quad (9)
\]
where \( Q_0, M_0, x_{x,0} \) are nominal values of \( Q, M, x_{x,0} \).

In virtue of Assumption 3, the weight parameter vector \( w \) of the basis functions can be initialized as
\[
\hat{w}_{n0} = \phi_0(p_n), \quad (10)
\]
for \( n = 1, 2, \ldots, N \), so that \( \hat{\phi}(x_1, \hat{w}_0) \approx \phi_0(x_1) \).

Although it may not be necessary to know the nominal parameters accurately in advance, use of prior information as possible can improve the transient performance in practice.

3. Design of the adaptive robust nonlinear controller

In this section, we show the design procedure of the adaptive robust nonlinear controller via the backstepping approach.

Step 1: Define the error signals of position \( x_1 \) and velocity \( x_2 \) as
\[
z_1 = x_1 - \hat{y}_r, \quad z_2 = x_2 - x_1, \quad (11)
\]
where \( z_1 \) is the virtual input to stabilize \( z_1 \). Substituting \( x_2 = z_2 + x_1 \) into the first row of Eq. (1), we have subsystem \( S_1 \) as follows:
\[
S_1: \dot{z}_1 = z_1 + z_2 - \dot{y}_r. \quad (12)
\]
The virtual input \( x_1 \) is designed here on the common PI control technique, to stabilize subsystem \( S_1 \) and to remove the offset of \( z_1 \).
\[
x_1 = -c_{1p}z_1 - c_{1i} \int_0^\infty z_1 \, dt + \dot{y}_r, \quad (13)
\]
where \( c_{1p} \gg 0, \, c_{1l} > 0 \).

Denote the Laplace operator as \( s \). Then, subsystem \( S_1 \) controlled by the virtual input \( x_1 \) can be expressed as
\[
z_1 = \frac{sz_2}{s^2 + c_{1p}s + c_{1i}}, \quad (14)
\]
Let \( h \) be the impulse response of transfer function \( s/(s^2 + c_{1p}s + c_{1i}) \). Then according to Theorem B.2 in Krstic et al. (1995), we have
\[
||z_1||_\infty \leq ||h||_1 ||z_2||_\infty. \quad (15)
\]
Therefore, if the velocity error \( z_2 \) is stabilized to a neighborhood of the origin, \( |z_2| \) can be made sufficiently small by a suitably designed \( ||h||_1 \).

Step 2: With Eqs. (1), (11) and (13), we have subsystem \( S_2 \) as
\[
S_2: \dot{z}_2 = c_{1p}(x_2 - \hat{y}_r) + c_{1l}(x_1 - y_r) - \dot{y}_r \quad + g + \phi(x_1)\dot{z}_2. \quad (16)
\]

To stabilize \( z_2 \), we design the control law as follows:
\[
l^2 = u_{stf} + u_{stl}. \quad (17)
\]
\[
u_{stf} = \frac{x_{x,0}}{\hat{\phi}(x_1, \hat{w})} - \frac{-\kappa_{21}\hat{g}_t z_2 - \kappa_{22}|x_{x,0}|z_2}{\hat{\phi}(x_1, \hat{w})}, \quad (18)
\]
\[
x_{x,0} = -c_2z_2 - c_{1p}x_2 - c_{1l}z_1 + c_{1p}\dot{y}_r + \dot{y}_r - \hat{g}_t, \quad (19)
\]
where \( c_2 > 0, \, \kappa_{21} > 0, \, \kappa_{22} > 0, \, u_{stf} \) and \( u_{stl} \) are the adaptive feedback linearization control term and the robust control term (nonlinear damping term) respectively. \( \hat{g}_t, \hat{w}_t \) are parameter estimates at time \( t \).

Eqs. (16)-(19) lead to
\[
\dot{z}_2 + c_2z_2 = (g - \hat{g}_t) + (\phi(x_1) - \hat{\phi}(x_1, \hat{w}))u_{stf} + \phi(x_1)u_{stl} \quad (20)
\]
Define the approximation error of the RBF network as
\[
\eta_t = \phi(x_1) - \hat{\phi}(x_1, \hat{w}^*) \quad (21)
\]
and the regression vector as
\[
\Phi_t' = [r(x_1 - p_1), \ldots, r(x_1 - p_N)] = [\phi_{t1}, \ldots, \phi_{tN}]. \quad (22)
\]
Then Eq. (20) can be rewritten as

\[ \dot{z}_2 = -c_2 z_2 - \ddot{g}_t - u_{st} \Phi_1^T \dot{w} + \eta_t u_{st} + \phi(x_1) u_{st}, \]

where the parameter errors at time \( t \) are defined as

\[ \ddot{w}_t = \ddot{w}_t - w^N, \quad \ddot{g}_t = \ddot{g}_t - g. \]  

Then we can update the parameters by the following adaptive law (Ioannou & Sun, 1996):

\[
\begin{cases}
0 & \text{for } \ddot{g}_t = \ddot{g}_t, \ z_2 < 0, \\
\dot{\ddot{g}}_t = \zeta c_2 & \text{for } \ddot{g}_t = \ddot{g}_t, \ z_2 > 0,
\end{cases}
\]

\[
\dot{w}_t = \begin{cases}
0 & \text{for } \ddot{w}_t = \ddot{w}_t, \ u_{st} \Phi_1 z_2 < 0, \\
\dot{\ddot{w}}_t = \zeta c_2 & \text{for } \ddot{w}_t = \ddot{w}_t, \ u_{st} \Phi_1 z_2 > 0,
\end{cases}
\]

where \( n = 1, 2, \ldots, N \), and \( \zeta \) is the adaptive gain. Notice that \( \dot{\ddot{g}}_t = 0 \) implies that the adaptive law is turned-off such that the controller is fixed.

4. Stability analysis

It is obvious that the overall error dynamics is a cascade of subsystems \( \mathcal{S}1 \) and \( \mathcal{S}2 \) described in Eqs. (14) and (23), respectively. And it is clear that if subsystem \( \mathcal{S}2 \) is stable so that the velocity error \( z_2 \) is stabilized to a neighborhood of the origin, then \( \|z_1\| \) can be made sufficiently small and the offset can be removed by the integrator.

Remark 1. All the results obtained in this section are local, since they are valid as long as the steel ball stays in the physically allowable operating region of \( x_1 \), i.e., the steel ball should not hit the electromagnet.

Remark 1 implies that it is also an important issue in practice to achieve a guaranteed transient performance of an adaptive controller for the magnetic levitation system. Since the parameters of \( \mathcal{S}1 \) described in Eq. (14) are fixed, it is sufficient to investigate the transient performance of the error signal \( z_2 \). Notice that the robust control term improves not only the ultimate control error, but also transient performance of \( z_2 \). This can be shown as follows:

\[
\frac{d}{dt} \left( \frac{z_2}{2} \right) = -c_2 z_2^2 - \ddot{g}_t z_2 + (\phi(x_1) - \phi(x_1, \dot{w}_t)) u_{st} z_2 + \phi(x_1) u_{st} z_2
\]

\[ \leq - \left( c_2 \right) \left( \frac{z_2}{2} \right)^2 \]

\[ - \left( \frac{c_2}{2} + \frac{\phi(x_1)}{\phi(x_1, \dot{w}_t)} (\kappa_{21} \ddot{g}_t + \kappa_{22} |x_{20}|) \right) \times |z_2| |z_2| - \psi_2 \]

where

\[ \psi_2 = \frac{|\ddot{g}_t| + |\ddot{w}_t| x_{20}/\phi(x_1, \dot{w}_t)}{c_2 + [\phi(x_1)/\phi(x_1, \dot{w}_t)](\kappa_{21} \ddot{g}_t + \kappa_{22} |x_{20}|)}.
\]

Notice that \( \phi(x_1)/\phi(x_1, \dot{w}_t) > 0 \) according to Assumption 2.

Since \( \psi_2 \) is continuous and uniformly bounded in \( X \), we have

\[ |z_2| \geq \psi_2 \Rightarrow \frac{d}{dt} \left( \frac{z_2}{2} \right) \leq -c_2 z_2^2 \]

and hence the transient performance of \( z_2 \) can be specified as (Krstic et al., 1996)

\[ |z_2(t)| \leq |z_2(0)| e^{-c_2 t} + \sup_{0 \leq t < T} |\psi_2(t)|. \]

Inspection of Eq. (28) shows that the transient performance of \( z_2 \) can be improved by the robust control term.

To investigate the ultimate bound of \( |z_2| \) which is improved by parameter adaption, we define a Lyapunov function as

\[ V = \frac{z_2^2}{2} + \frac{\ddot{g}_t^2}{2\zeta} + \frac{\dot{w}_t^2}{2\zeta}, \]

where \( \zeta > 0 \).

Then, we have

\[ \dot{V} = z_2 \ddot{z}_2 + \frac{\ddot{g}_t}{\zeta} \frac{\ddot{z}_2}{\zeta} + \frac{\dot{w}_t^2}{\zeta} \dot{w}_t \]

\[ = z_2 (c_2 z_2^2 - \ddot{g}_t - u_{st} \Phi_1^T \dot{w}_t + \eta_t u_{st} + \phi(x_1) u_{st}) - \frac{\ddot{g}_t}{\zeta} \frac{\ddot{z}_2}{\zeta} + \frac{\dot{w}_t^2}{\zeta} \dot{w}_t \]

\[ \leq -c_2 z_2^3 + \eta_t |x_{20}| z_2 - \phi(x_1) \kappa_{21} \ddot{g}_t + \kappa_{22} |x_{20}| z_2^2 \frac{\phi(x_1, \dot{w}_t)}{\phi(x_1, \dot{w}_t)} \]

\[ \leq -\left( c_2 + \frac{\phi(x_1)}{\phi(x_1, \dot{w}_t)} (\kappa_{21} \ddot{g}_t + \kappa_{22} |x_{20}|) \right) z_2^3 - \psi_2 \]

(33)
where

$$
\delta_2 = \frac{|\eta_t z_{20}/\hat{\phi}(x_1, \hat{\nu}_1)|}{c_2 + |\psi(x_1)/\hat{\phi}(x_1, \hat{\nu}_1)| (K_{21} \hat{g}_t + K_{22} |z_{20}|)}.
$$

(34)

With Assumption 1 and Remark 1 in mind, it is trivial to show that $\delta_2$ is continuous and uniformly bounded in $X = \{x_1 | 0 < x_1 < x_{1M}\} \subset \mathbb{R}$ as

$$
0 \leq \delta_2 < \frac{\eta_t}{K_{22} |\hat{\phi}(x_1)|} \leq \frac{\epsilon}{K_{22} |\hat{\phi}(x_1)|}.
$$

(35)

Therefore, we have

$$
|z_2| > \delta_2 \Rightarrow \dot{V} < 0.
$$

(36)

Based on the above discussions, we have the following lemma for $\mathcal{S}_2$ in $X$.

**Lemma 1.** Let assumptions 1–3 hold. When the control law (17)–(19) and the adaptive law (25) and (26) are applied to subsystem $\mathcal{S}_2$, all the internal signals of subsystem $\mathcal{S}_2$ are uniformly bounded and the following results hold:

$$
|z_2(t)| \leq |z_2(0)| e^{-c_2 t/2} + \sup_{0 \leq t < \infty} |\psi_2(t)|,
$$

$$
\nu \leq \hat{\nu}_1 \leq \bar{\nu}, \quad g \leq \hat{g}_t \leq \bar{g} \quad \text{for all } t \geq 0,
$$

and

$$
|z_2(t)| \leq \delta_2(t) \leq \frac{\epsilon}{K_{22} |\hat{\phi}(x_{1M})|} \quad \text{as } t \to \infty.
$$

Finally, Lemma 1 and Eqs. (14) and (15) lead to the following result.

**Theorem 1.** Let assumptions 1–3 hold. All the internal signals of the overall control system are uniformly bounded, and under improved transient performance the ultimate magnitude of the position error $z_1$ can be made sufficiently small with zero offset.

It should be pointed out that owing to the existence of the robust control term, the stability of the control system is still ensured even when the adaptive law is turned-off ($\lambda = 0$) such that the controller is fixed. In this case, the control law (17)–(19) becomes

$$
u_{st} = \frac{\ddot{z}_2}{\hat{\phi}(x_1, \hat{\nu}_0)}, \quad u_{st} = -\frac{K_{21} \hat{g}_0 z_2 - K_{22} |\ddot{z}_2|}{\hat{\phi}(x_1, \hat{\nu}_0)}.
$$

(37)

$$
\ddot{z}_2 = -c_2 z_2 - c_{1p} x_2 - c_{1z} z_1 + c_{1p} \ddot{y}_r + \ddot{y} - \hat{g}_0,
$$

(38)

where $\hat{g}_0$ is the nominal gravity acceleration, and $\hat{\nu}_0$ is the fixed weight parameter vector of the RBF network, which is initialized so that $\hat{\phi}(x_1, \hat{\nu}_0) \approx \phi_0(x_1)$ (see Assumption 3). In this case, the transient performance of $z_2$ becomes to the following.

**Corollary 1.** Let Assumptions 1–3 hold. When the adaptive law is turned-off such that the control law (17)–(19) is fixed based on the nominal parameters, all the internal signals of subsystem $\mathcal{S}_2$ are uniformly bounded and the transient performance of $z_2$ is specified as

$$
|z_2(t)| \leq |z_2(0)| e^{-c_2 t/2} + \sup_{0 \leq t \leq \tau} |\psi_2(t)|,
$$

where

$$
\psi_2 = \frac{\hat{g}_0 - g}{c_2/2 + (\phi(x_1)/\hat{\phi}(x_1, \hat{\nu}_0))(K_{21} \hat{g}_0 + K_{22} |\ddot{z}_2|)},
$$

$$
\hat{\nu}_0 = \phi(x_1) - \hat{\phi}(x_1, \hat{\nu}_0).
$$

**Remark 2.** According to Lemma 1, Corollary 1, and Lemma C.4 in Krstic et al. (1995), we can also conclude that the overall error system which is a cascade of subsystems $\mathcal{S}_1$ and $\mathcal{S}_2$ described in Eqs. (14) and (23), is input-to-state stable.

**Remark 3.** Actually, the desired value of coil current $i$ is computed by

$$
i = (u_{st} + u_{ad})^{0.5}
$$

(39)

and it is required here $(u_{ad} + u_{st}) > 0$. Empirically this inequality is satisfied in generic cases if the values of the controller parameters $c_{1p}, c_{1z}, c_2, K_{21}, K_{22}$ and the magnitude of desired acceleration $\bar{y}_r$ are not chosen to be extremely large.

5. Experimental Results

The performance of the proposed adaptive robust nonlinear control system is verified through experimental studies on the magnetic levitation system shown in Fig. 1, whose parameters are given in Table 1. The physically allowable operating region of the steel ball shown in Fig. 1 is limited to $X = \{x_1 | 0 \leq x_1 \leq 0.013 \text{ m}\}$.

Design parameters for the experimental studies are given as follows.

**Nominal system parameters:**

$$
M_0 = 0.3 \text{ kg}, \quad g_0 = 9.0 \text{ m/s}^2, \quad X_{\infty} = 0.0020 \text{ m},
$$

$$
Q_0 = 0.00030 \text{ H m}.
$$

(40)

Center positions of Gaussian basis functions (five basis functions are used here):

$$
p_n = 0.00325(n - 1)(\text{m}), \quad n = 1, \ldots, 5.
$$

(41)

<table>
<thead>
<tr>
<th>Table 1</th>
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<tr>
<td>Physical parameters of the system</td>
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<td>$M$</td>
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<td>$g$</td>
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<td>$Q$</td>
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position tracking problem of a gravity-biased one degree-of-freedom magnetic levitation system which is widely studied in the literature. Stability and transient performance of the control system are analyzed theoretically, and experimental results show that the performance of the designed controller is very satisfactory. Our future study is to extend the basic idea to the case where the current feedback power amplifier is removed. This is much more challenging since in this case the system dynamics is governed by a third-order nonlinear model which is usually not in canonical form.

6. Conclusions

In this paper, we proposed an adaptive robust nonlinear controller via backstepping design approach, for

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**References**


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