

Fault Tolerant Neuro-Robust Position Control of DC Motors

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ABSTRACT

DC motors are widely used in industry such as mechanics, robotics, and aerospace engineering. In this paper, we present a high performance control method for position control of DC motors. Fault-tolerant control model are also addressed to combine with neuro-robust control approach. It is shown that with the proposed control algorithms, external disturbances and coupled dynamics inherent in the system are effectively compensated using neural network unit in which no analytical estimation on the upper bound of the reconstruction error and uncertainties is needed. Simulations results of the position control also confirm the effectiveness of the proposed methods.

Keywords: Fault-Tolerant, Neuro-Robust, Position Control, DC Motors

1. Introduction

In this paper, we proposed a neuro-robust position control of DC motors incorporating a fault-tolerant control model with the condition of parameter uncertainty and unknown load torque. DC motors are widely used in industry such as mechanics, robotics, and aerospace engineering. In recent years, some methods are applied for the position control of DC motors. For example, an adaptive PID control tuning was proposed to cope with the control problem for a class of uncertain chaotic systems with external disturbance [1]. Sliding mode control (SMC) is one of the popular strategies to deal with uncertain control systems [2-4]. Based on certain assumptions, various control approaches, such as model-based control, nonlinear inverse control, and neural network based control (and others) have been proposed [5-6].

This work is concerned with position control of DC motors by neuro-robust control. A nonlinear model is considered incorporate with fault-tolerant model in which modelling uncertainties and nonlinearities are explicitly addressed. The NN unit is designed to cope with the disturbances and coupled dynamics. Unlike traditional NN based method, there is no need to analytically estimate the upper bound of the reconstruction error and uncertainties in the proposed approach. Both theoretical analysis and simulation studies verify the effectiveness of the control algorithms.

2. Problem Formulation

2.1. Modeling of DC Motors

The DC motors dynamics is given by

$$\frac{K_m}{rR}V - \frac{J_m}{r^2}\ddot{q} - \frac{B_m + K_b K_m / R}{r^2}\dot{q} - Q(t) = 0 \quad (1)$$

where q is the position of link, K_m is the torque constant, J_m is the motor inertia, B_m is the damping coefficient, K_b is the back emf constant, R is the armature resistance, r is the gear ratio, $Q(t)$ is the load torque, and V is the control input in voltage [7].

Our control objective is to make the position q tracking to the desired position q_d . From (1), we have

$$\ddot{q} = \frac{rK_m}{J_m R}V - \frac{B_m + K_b K_m / R}{J_m}\dot{q} - \frac{r^2}{J_m}Q(t) \quad (2)$$

For later development, we can express (2) in the following compact form with $x = q$ as

$$\ddot{x} = bV + L(\bullet) \quad (3)$$

where

$$b = \frac{rK_m}{J_m R} \quad (4)$$

$$L(\bullet) = -\frac{B_m + K_b K_m / R}{J_m}\dot{q} - \frac{r^2}{J_m}Q(t) \quad (5)$$

A direct measurement of the load torque is difficult

because high cost equipment is required. Thus, the load torque $Q(t)$ is usually considered to be unknown. The control objective is to design V so that the actual position trajectory q tracks the desired q_d asymptotically.

2.2. Fault Tolerant Control Model

As actuator failures represent the most typical and devastate faults, we should explicitly address such faults in control design. The preceding control failures can be modeled for each control by the following model

$$U_a = \Delta(t, t_1^{L1}, t_2^{L1}, \dots, t_n^{L1}) U_c + D(t, t_1^{L2}, t_2^{L2}, \dots, t_n^{L2}) \quad (6)$$

with

$$\Delta(t, t_1^{L1}, t_2^{L1}, \dots, t_n^{L1}) = \begin{bmatrix} \delta_1(t - t_1^{L1}) \\ \delta_2(t - t_2^{L1}) \\ \vdots \\ \delta_n(t - t_n^{L1}) \end{bmatrix} \quad (7)$$

$$D(t, t_1^{L2}, t_2^{L2}, \dots, t_n^{L2}) = \begin{bmatrix} d_1(t - t_1^{L2}) \\ d_2(t - t_2^{L2}) \\ \vdots \\ d_n(t - t_n^{L2}) \end{bmatrix} \quad (8)$$

where U_a is the applied controller, U_c is the demanded control to be designed, $0 \leq \delta_i(\cdot) \leq 1$ and $|d_i(\cdot)| \leq d_0 < \infty$ are the actuation health indicator and un-adjustable portion of the actuator. In general, $t_i^{F1} \neq t_j^{F1}, t_i^{F2} \neq t_j^{F2} (\forall i \neq j)$ and $t_i^{F1} \neq t_i^{F2}$. It should be mentioned that the proposed fault model includes the commonly used fault model as a special case [8,9]. With the proposed actuator fault model (6), we can model all the possible actuation faults as mentioned earlier with δ_i and d_i defined properly, as follows:

Fault Case 1) $\{\delta_i(\cdot) = 1; d_i(\cdot) = 0\}$: healthy

Fault Case 2) $\{\delta_i(\cdot) < 1 \text{ but } \delta_i(\cdot) \neq 0; d_i(\cdot) = 0\}$: fading power but partially controllable

Fault Case 3) $\{\delta_i(\cdot) = 0; d_i(\cdot) = 0\}$: completely shut down

Fault Case 4) $\{\delta_i(\cdot) = 0; d_i(\cdot) \neq 0\}$: completely uncontrollable

Fault Case 5) $\{\delta_i(\cdot) < 1 \text{ but } \delta_i(\cdot) \neq 0; d_i(\cdot) \neq 0\}$: fading power but partially controllable with uncontrollable portion.

Most existing fault-tolerant control methods such as [8,9] are based on constant $\Delta(\cdot)$ and $D(\cdot)$ which is practically restrictive. In our design, we treat both $\Delta(\cdot)$ and $D(\cdot)$ as completely unknown time-varying. Presently, there is no technique available to anticipate/predict such faults precisely. We design a control scheme that does

not explicitly use any information about $\delta_i, d_i, t_i^{F1}, t_i^{F2}$. Namely, we assume that not only the type and the magnitude of the faults are unknown, the time profile of fault occurrence are also unpredictable.

Let us define $u_a = V$, and substitute for u_a from (6), we get

$$\begin{aligned} \ddot{x} &= bu_a + L(\bullet) \\ &= b(\Delta u_c + d) - \frac{B_m + K_b K_m / R}{J_m} \dot{q} - \frac{r^2}{J_m} Q(t) \end{aligned} \quad (9)$$

which can be expressed as

$$\ddot{x} = gu_c + \eta(\bullet) \quad (10)$$

where

$$\begin{aligned} g &= b\Delta \\ \eta(\bullet) &= bd - \frac{B_m + K_b K_m / R}{J_m} \dot{q} - \frac{r^2}{J_m} Q(t) \end{aligned} \quad (11)$$

Thus, the model of DC motor has been constructed, and the u_c is the control input. We will consider the case that all the actuator partially loses its effectiveness in that $\delta_i(\cdot) < 1$ but $\delta_i(\cdot) \neq 0$ in the following control design.

3. Control Design

As the first step, we define the position acking error

$$e = x - x_d \quad (12)$$

where x_d is the desired position, and the filtered error variable

$$s = \dot{e} + \beta e. (\beta > 0) \quad (13)$$

Because of (7), it is seen that the control objective is realized as long as s is driven to zero as time goes by. Therefore, we focus on designing u to stabilize s . From (3) and (5) we have

$$\dot{s} = gu_c + \eta(\bullet) - \ddot{x}_d + \beta \dot{e} \quad (14)$$

Due to the existence of the uncertainties, as lumped by $\eta(\bullet)$, traditional model-based control is not applicable. In this work, we design the neuro-robust control scheme based on the unavailable part $\eta(\bullet)$, which is to compensated by the following neural network unit,

$$\eta(\bullet) = f_{NN} + \varepsilon = w^T \varphi + \varepsilon \quad (15)$$

where $w^T \in R^{3 \times l}$, $\varphi(\bullet) \in R^{l \times 1}$ are the optimal weight matrix and basic function vector of the neural network, respectively, and $\|\varepsilon\| \leq E_0 < \infty$ is the reconstruction error with unknown upper bound. For this case, we construct the following controller

$$u_c = g^{-1}(-\beta \dot{e} - ks + \ddot{x}_d + u_n) \quad (16)$$

where $k > 0$ is control parameter chosen by designer. With the control scheme (16), it is seen that the closed-

loop dynamics become

$$\dot{s} = -ks + \eta + u_n \tag{17}$$

the NN based compensation is given as follows,

$$u_n = -[\hat{w}^T \varphi + u_{rb}] \tag{18}$$

with

$$\hat{w} = \int_0^t \varphi(\bullet) s^T(\tau) d\tau, u_{rb} = \left[\int_0^t \|s\| d\tau \right] \text{sgn}(s(t))$$

$$\varphi_i = \frac{1 - e^{-\alpha_i \|X\|}}{1 + e^{-\alpha_i \|X\|}}, \left(X = [r \ \dot{r} \ \theta \ \dot{\theta} \ \phi \ \dot{\phi}], i = 1, 2, \dots, l \right)$$

The overall control block diagram is shown in **Figure 1**. To address the stability, we consider the following Lyapunov function candidate,

$$V = \frac{1}{2} s^T s + \frac{1}{2} \text{tr}(\tilde{w}^T \tilde{w}) + \frac{1}{2} \left(E_0 - \int_0^t \|s\| d\tau \right)^2 \tag{19}$$

where $\tilde{w} = w - \hat{w}$, it can be shown that

$$\begin{aligned} \dot{V} &= s^T \dot{s} - \text{tr}(\tilde{w}^T \dot{\hat{w}}) + \left(E_0 - \int_0^t \|s\| d\tau \right) (-\|s\|) \\ &\leq -ks^T s + s^T (w^T \varphi(\bullet) + \varepsilon) - s^T (\hat{w}^T \varphi(\bullet)) - s^T u_{rb} \\ &\quad + \text{tr}(w - \hat{w})^T (-\dot{\hat{w}}) - \left(E_0 - \int_0^t \|s\| d\tau \right) (\|s\|) \\ &= -ks^T s + \text{tr}[(w - \hat{w})^T (\varphi(\bullet) s^T - \dot{\hat{w}})] + s^T (\varepsilon - u_{rb}) \\ &\quad - \left(E_0 - \int_0^t \|s\| d\tau \right) (\|s\|) \end{aligned} \tag{20}$$

Note that $s^T (\varepsilon - u_{rb}) \leq \left(E_0 - \int_0^t \|s\| d\tau \right) (\|s\|)$, it follows that

$$\dot{V} \leq -k_2 s^T s \leq 0$$

Thus

$$s \in L_\infty \cap L_2 \cap L_1, \hat{w} \in L_\infty$$

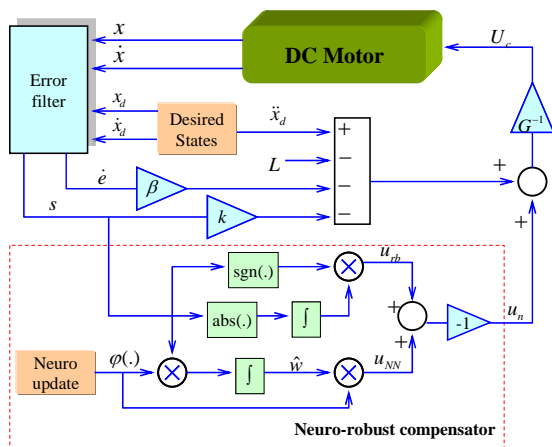


Figure 1. Block diagram of the proposed neuro-robust controller.

We can also show that s is uniformly continuous because $\dot{s} \in L_\infty$. By Babalart lemma, we conclude that $s \rightarrow 0$ as $t \rightarrow \infty$, then $e \rightarrow 0$, and $\dot{e} \rightarrow 0$, as $t \rightarrow \infty$, i.e: $q \rightarrow q_d$ and $\dot{q} \rightarrow \dot{q}_d$ as $t \rightarrow \infty$.

Remark 1. The control scheme, consisting of (16) and (18), has simple structure, and does not involve analytical estimation of the upper bound on the reconstruction error, making the design process simple and easy for implementation easy.

4. Simulation Results

To verify the effectiveness of the controller, a numerical simulation study was conducted. The following functions were used in the simulation,

$$\begin{aligned} B_M &= 2.68 \times 10^{-5} \text{ Nms}; K_b = 0.0603 \text{ Vs}; \\ K_m &= 0.060438586 \text{ Nm/A}; R = 1.16 \ \Omega; \\ J_m &= 0.0000134 \text{ Kgm}^2; r = 1 \end{aligned}$$

Simulation results are given in **Figure 2** and **Figure 3**, where **Figure 2** is a plot of the position tracking. The initial values are all set 0 at the very beginning for the two figures. The actual position is tracking to the desired position very quick and smooth in both cases. In first case, a one time position tracking is set, and in the second case, there is one more desired position set after the 4th second. **Figure 3** is the tracking error for both position tracking. Note that although precise descriptions of

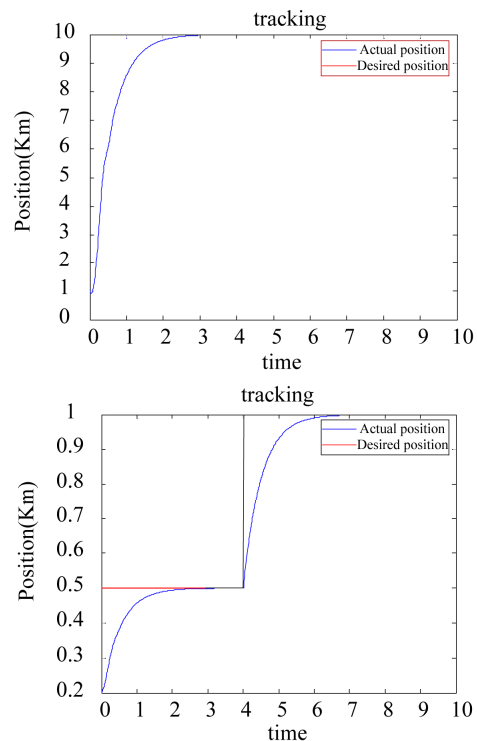


Figure 2. Tracking process.

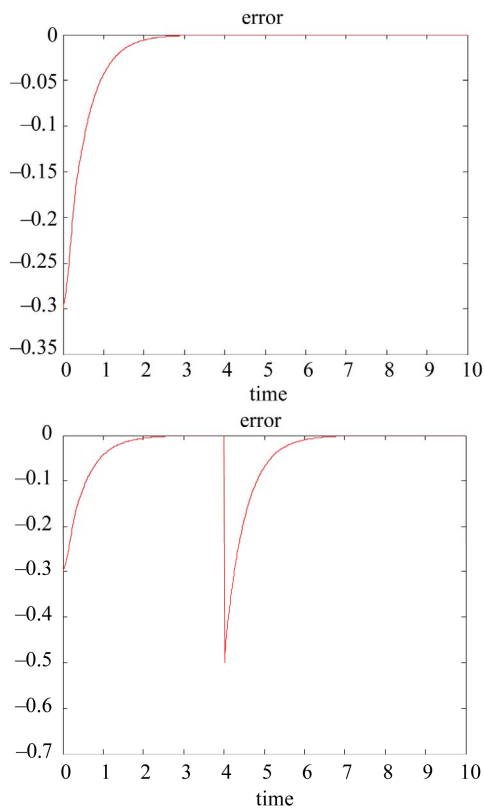


Figure 3. Tracking error.

system dynamics and external disturbances are unavailable, good tracking precision via the proposed neuro-robust adaptive control still maintains with smooth control action and satisfactory position tracking

5. Conclusions

The paper explored the fault-tolerant control problem of DC motors. Using neuro-robust approach, control algorithms achieve high precision position tracking of DC motors under uncertainties and disturbances. The salient feature of the proposed method lies in its flexibility and simplicity in design and implementation. There is no need to redesign or reprogram the control scheme for the

different conditions, and no need of analytical estimation on the upper bound of the reconstruction error and uncertainties. A numerical example was simulated as a verification of the effectiveness of the proposed control algorithms.

REFERENCES

- [1] W. D. Chang and J. J. Yan, "Adaptive Robust PID Controller Design Based on a Sliding Mode for Uncertain Chaotic Systems," *Chaos Solitons & Fractals*, Vol. 26, No. 1, 2005, pp. 167-175. [doi:10.1016/j.chaos.2004.12.013](https://doi.org/10.1016/j.chaos.2004.12.013)
- [2] J. Y. Hung, W. Gao and J. C. Hung, "Variable Structure Control: A Survey," *IEEE Transactions on Industrial Electronics*, Vol. 40, No. 1, 1993, pp. 2-22. [doi:10.1109/41.184817](https://doi.org/10.1109/41.184817)
- [3] K. D. Young, V. I. Utkin, and Ü. Özgüner, "A control Engineer'S Guide to Sliding Mode Control," *IEEE Transactions on Control Systems Technology*, Vol. 7, No. 3, 1999, pp. 328-342. [doi:10.1109/87.761053](https://doi.org/10.1109/87.761053)
- [4] A. S. I. Zinober, "Variable Structure and Lyapunov Control," Springer-Verlag, Berlin, 1994. [doi:10.1007/BFb0033675](https://doi.org/10.1007/BFb0033675)
- [5] A. Calise and R. Rysdyk, "Nonlinear Adaptive Flight Control Using Neural Networks," *Control Systems Magazine*, Vol. 18, No. 6, 1998, pp. 14-25. [doi:10.1109/37.736008](https://doi.org/10.1109/37.736008)
- [6] F. Lewis, "Nonlinear Network Structures for Feedback Control," *Asian Journal of Control*, Vol. 1, No. 4, 1999, pp. 205-228. [doi:10.1111/j.1934-6093.1999.tb00021.x](https://doi.org/10.1111/j.1934-6093.1999.tb00021.x)
- [7] H.-L. Choi, Y.-H. Chang, Y. Oh and J.-T. Lim, "On Robust Position Control dc Motor by PID Controller and Its Application to Humanoid Robot Arms," *Proceedings of the 17th IFAC World Congress*, Seoul, 6-11 July 2008.
- [8] J. D. Boskovic, R. K. Prasad and R. K. Mehra, "Reconfigurable Fault-tolerant Flight Control: Algorithms, Implementation and Metrics," AIAA Guidance, Navigation and Control Conference and Exhibit, Keystone, 21-24 August 2006.
- [9] M. Bodson and J. Groszkiewicz, "Multivariable Adaptive Algorithms for Reconfigurable Flight Control," *IEEE Transactions on Control Systems and Technology*, Vol. 5, No. 2, 1997, pp. 217-229. [doi:10.1109/87.556026](https://doi.org/10.1109/87.556026)