Improved wavelet cerebellar model articulation controller for precision positioning of piezo-driven stage

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Abstract. This paper proposes an improved wavelet cerebellar model articulation control system (IWCMACS) to control precision positioning of the linear piezoelectric motor (LPM). The proposed system combines the improved wavelet cerebellar articulation model controller (IWCMAC) with the estimated bound compensator controller to obtain high-precision positioning for applications requiring accuracy within micrometer or nanometer range. In this research, the momentum and proportional factors are added into learning algorithm to escape from local minima points and speed up convergence of the system. The Lyapunov-Like Lemma is used to estimate error bound to guarantee the stability of the system. The experimental results for the piezo-driven stage conclude the effectiveness and applicability of the proposed control system for model-free nonlinear.

1. Introduction
Together with development of nanotechnology, linear piezoelectric motors with their superior properties such as small dimension, high force at low speed, high-holding force, silence and nanometer displacement resolution have been more popular in many industrial applications and attracted much attention of researchers [1-3]. However, the dynamic equation of the LPM is complex and nonlinear [4] so the model-based controllers can’t obtain favorable performance and robust for the entire domain of working [5]. To overcome this problem, many intelligent controller have been developed for controlling the LMPs in the recent years such as sliding mode controllers [6], neural network [7], CMAC and wavelet cerebellar model articulation controller (WCMAC) [8-10]. However, the local minima problems is not treated and discussed in these researches.

In this research, the improved wavelet cerebellar model articulation controller (IWCMAC) combines with the estimated bound compensator controller are used to control piezo-driven stage to obtain precision positioning. Where, the IWCMAC is used to imitate the ideal controller which is affected by uncertainties and disturbances to minimize error function and avoid local minima. Furthermore, the estimated bound compensator controller is used to attenuate effects of disturbances and noises to the stability of the system.

This rest of the paper is organized as follows: Section 2 describes the precision positioning system and proposed control system. Section 3 describes the structure of proposed control system, which consists of the training and avoiding local minima method. Section 4 provides the experimental results and discussion. Section 5 is conclusion and future research.
2. The precision positioning system dynamic description

The structure of the precision positioning system is represented in figure 1. The system has main parts such as, XY stage base controled by LPMs, driver AB5, distance sensors, 1711 PCI card, PC with matlab software.

![Figure 1. The structure of the precision positioning system.](image)

The dynamic equation of LPMs including hysteresis and stiffness behavior is described in detail in [7] and has the following equation (1).

\[
\ddot{a} = \frac{D_a}{M_a} \dot{a} + \frac{K_{ea}}{M_a} u_a - \frac{F_{la} + F_{ha}}{M_a}
\]

(1)

where \( a \) is x, y for the x-axis, y-axis respectively; \( M_a \) is the effective mass of the moving stage; \( \ddot{a}, \dot{a}, a \) are acceleration, velocity and displacement, respectively; \( D_a \) is the friction coefficient; \( F_{la} \) is an unknown external disturbance force; \( K_{ea} \) is the voltage-to-force coefficient; \( u_a \) is the control voltage of the LPMs; \( F_{ha} \) is the hysteresis frictional force given as equation (2) [7].

\[
F_{ha} = ab + \beta \frac{db}{dt} + \gamma \dot{a}
\]

(2)

where \( b \) is the average deflection of the elastic bristles between two contact surfaces of rigid bodies; \( \alpha, \beta, \gamma \) are positive constants depending on the bristle stiffness, bristle damping, and viscous damping coefficient respectively.

In general, the parameters of the LPMs such as \( D_a, F_{la} \) and especially \( F_{ha} \) can’t be obtained or measurable exactly. Therefore, from the point of view of control system, these terms are considered as uncertainties or disturbances and the controllers must be designed to compensate the difference between nominal and practical value. So the dynamic equation of the LPMs can be rewritten as equation (3)

\[
\ddot{d} = F_d(d) + G_d(d)u + UD(d)
\]

(3)

where \( F_d(d) = -\frac{D_a}{M_{a0}}, G_d(d) = \frac{K_{ea0}}{M_{a0}}, u \) are nominal nonlinear vector, control gain and the control voltage of the LPMs, respectively. \( UD(d) = -\frac{F_{ha0} + F_{la0}}{M_{a0}} + f(D, F_{ha}, F_{la}, t) \) denote nominal hysteresis frictional force, nominal external force, uncertainties and disturbances which are assumed to be bounded, \( d = [d, d]^T \) is the state vector. The tracking error is defined as equation (4)
\[ e_\theta(t) = d_\theta(t) - d(t) \]  

Assuming that, an error sliding surface is described as equation (5) 

\[ s(t) = \dot{e}_\theta(t) + K_1 e_\theta(t) + K_2 \int_0^t e_\theta(\tau)d\tau. \]  

where: \( K_1 \) and \( K_2 \) are nonzero positive constants.

In case the parameters of the system are definitely defined and the external torque is measurable, a feedback linearization ideal controller can be designed as equation (6) [9]

\[ u_{\text{ideal}} = \frac{1}{G_\theta(d)} \left[ \hat{\theta}_\theta - F_\theta(d) - UD(d) + K_1 \hat{e}_\theta + K_2 e_\theta \right] \]  

The error dynamic equation is obtained by substituting (6) into (3) 

\[ \dot{s} = \dot{e}_\theta + K_1 e_\theta + K_2 \dot{e}_\theta = -F_\theta(d) - G_\theta(d)u - UD(d) + \dot{\hat{\theta}}_\theta + K_1 \dot{e}_\theta + K_2 e_\theta = 0. \]  

The convergence of error dynamic equation (7) is guaranteed under condition that the constants \( K_1 \) and \( K_2 \) are chosen to correspond to the Hurwitz polynomial coefficients. The ideal controller in (6), however, can’t be obtained since \( UD(d) \) is immeasurable or exactly known in the practical applications.

To deal with the uncertainties and disturbances, \( UD(d) \), a proposed IWCMAC control system is depicted in figure 2. This proposed controller combines a main controller \( u_{\text{IWCMAC}} \) and a estimated bound compensator controller \( u_{\text{CC}} \). Where \( u_{\text{IWCMAC}} \) is developed to imitate the ideal controller and escape from sticking in a local minima, \( u_{\text{CC}} \) is designed to dispel the effects of uncertainties and disturbances during learning. The total proposed control system has following equation (8).

\[ u = u_{\text{ideal}} - u_{\text{IWCMAC}} + u_{\text{CC}} \]  

**Figure 2.** The structure of the proposed control system.

3. The improved wavelet cerebellar model articulation controller

3.1. The structure of WCMAC

The WCMAC with its fast learning and good generalization capability places an important role to learn uncertainties \( UD(d) \) to minimum error sliding surface. The structure of the WCMAC is depicted
in figure 3 includes input Space $S$, association memory space $A$, receptive field space $R$, weight memory space $W$ and output spaces $O$. The signal propagation in the WCMAC is presented as follows [9].

3.2. The online learning rule

The varying load torque and the unknown lumped uncertainties $UD(d)$ are learned by the WCMAC $u_{WCMAC}$ with approximation error $\varepsilon$ as equation (9).

$$D(x) = \frac{1}{G(x)} u_{WCMAC}(S, w_{kj}, m_{ik}, \sigma_{ik}) + \varepsilon = \sum_{j=1}^{nj} \sum_{k=1}^{nk} \sum_{i=1}^{ni} \mu_{ik} (S_i)$$

(9)

The error function and the learning algorithm and compute parameters of the controller are described in detail in [9]. However, the weakness of this algorithm is that it may stuck in local minima points [11].

To avoid sticking in a local minima, the standard back propagation algorithm is modified by adding momentum term $\rho$ and propotional term $\nu$ for calculating new parameters of the controller [12]. The momentum term places an important role in preventing the network trap in to local minima and the propotional term speed up the convergence as the activation having flat slope. So the new update rules of the IWCMAC as equation (10), (11) and (12).

$$\Delta w_{ki}(t) = \Delta w_{ki}(t) + \rho \Delta w_{ki}(t-1) + \nu(d - d_k)$$

(10)

$$\Delta m_{kj}(t) = \Delta m_{kj}(t) + \rho \Delta m_{kj}(t-1) + \nu(d - d_k)$$

(11)

$$\Delta \sigma_{kj}(t) = \Delta \sigma_{kj}(t) + \rho \Delta \sigma_{kj}(t-1) + \nu(d - d_k)$$

(12)

3.3. The estimated bound compensator controller

The most useful property of IWCMAC is to learn linear or nonlinear functions through learning capability. In (9), the approximation error $\varepsilon$ is assumed to be bounded by a positive $B$. if error bound $B$ is assumed to be a constant during the operation then the compensator controller is designed
following the sliding mode theory to compensate for the effect of the approximation error due to uncertainties and disturbances as equation (13)

\[ u_{CC} = -G_o^{-1}(d)\hat{B}\text{sgn}(s) \]  

(13)

However, this bound parameter is immeasurable in practical applications. Therefore, an error bound estimation is developed to estimate this bound and given by estimation law as equation (14) [10].

\[ \hat{B} = \eta_B \|s\| \]  

(14)

In conclusion, the proposed system IWCMAC is represented in (9), the parameters \(\hat{w}, \hat{m}\) and \(\hat{\sigma}\) of which are adjusted and updated online (10)-(12). Moreover, the estimated bound compensator controller \(u_{CC}\) is given in (13) with bound estimation law as (14). The IWCMAC control system can be guaranteed to be stable in the Lyapunov-Like Lemma sense [13].

4. Experimental results

An image of the experimental equipment of the precision positioning system is showed in figure 4. To illustrate the superior of the proposed control system, the experimental results of the proposed control system and the proportional–integral-derivative (PID) controller are provided to further demonstrate the effectiveness of the proposed control system over PID.

The parameters of the nominal model of the drive system are given as:

- \(M_\omega = 5kg\), \(D_\omega = 66[N\text{.sec}/m]\), \(K_{E=0} = 3[N/Volt]\), \(\eta_w = 0.005\), \(\eta_m = 0.005\), \(\eta_D = 0.001\), \(K_1 = 0.041\), \(K_2 = 0.055\), \(\eta_k = 11\), \(\nu = 0.05\), \(\rho = 0.96\), \(K_p = 0.074\), \(K_i = 0.0002\), \(K_o = 0.0001\)

\(S = [-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0]\)

Sample time = 0.01s

![Figure 4. Image of practical control system.](image)

The experimental results of the PID controller and the IWCMAC due to sinusoidal and periodic step commands are depicted in figure 5 and figure 6, respectively.
Figure 5. Experimental results of PID and IWCMAC controller due to sinusoidal command. (a) Tracking response. (b) Error response. (c) Control signal.
Figure 6. Experimental results of PID and IWCMAC controller due to periodic step command. (a) Tracking response. (b) Error response. (c) Control signal.

The experimental results due to sinusoidal and periodic step commands show that the IWCMACS can work well in realtime applications. Comparing to PID controller, the better performances are obtained such as small convergence error and time, small voltage control signal at steady state and stability for a long time. These results once again confirm the effectiveness of the proposed system.
5. Conclusion and future works
In this paper, the IWCMAC system was proposed to control the precision positioning for piezo-driven stage. The proposed control system is composed by the IWCMAC and the estimated bound compensator controller. The parameters of the proposed IWCMAC system are tuned on-line and the system’s stability has been proven in the Lyapunov-Like Lemma sense. In addition, the effectiveness of the proposed control system has proved by the experimental results. Furthermore, the nominal nonlinear vector and control gain $F_0(d)$ and $G_0(d)$ non-essential to know exactly. If there are differences between nominal and practical parameters, they belong to uncertainties, $UD(d)$. Consequently, the proposed control system is available for model-free nonlinear control designs. However, to enhance the performance index, the robust controller should be investigated and added to guarantee the robustness of the all system in working space.

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