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Design and Implementation of Advanced Digital Controls for Piezo-Actuated Systems using Embedded Control Platform

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Abstract: This paper presents design of an advanced digital control method and implementation on an embedded control platform for precision tracking of piezo-actuated systems. The proposed control method consisting of neural control and repetitive control aims to achieve good performance for repetitive tracking tasks and robustness for uncertain parameters change. A FPGA based embedded controller, CompactRIO, is applied to realize such a complicated control algorithm under LabVIEW programming environment. With careful consideration of implementation issues involved in the controller design process, the experimental results demonstrate the effectiveness of the method and verify the feasibility of using embedded hardware for advanced controls implementation.

Keywords: Piezo-Actuated Systems, Advanced Control, Embedded Control Platform

1 Introduction

In recent years, piezo-actuated systems have been widely accepted as a useful technology followed by prompt development of materials and manufacturing processes. Various commercial products exist in diverse engineering applications including micro/nano positioning stages [1] ultra-precision machine tool [2] and measurement devices [3,4] adaptive structures [5,6] biomedical and consumer electronics [7] and so on.

In the recent competitive market, developing specific systems using embedded hardware such as Digital Signal Processor (DSP) and Field Pro-grammable Gate Array (FPGA) is a very popular solution to compact the real-time system design and optimize the maximum economic profits with less maintenance difficulties. For piezo-actuated systems Proportional-Integral-Derivative (PID) control has been extensively applied as a quick servo algorithm [3,4,8,9,10,11,12] for hardware-in-the-loop testing, due to its simplicity and easy implementation. However, one vital drawback of PID control is its limited ability to deal with nonlinearity and uncertainty commonly existed in piezo-actuated systems. For this reason a great number of advanced control methods and experimental results based on floating point control platforms [2,13,14,15] has been presented, to further improve the sys-tem performance and robustness subject to a variety of industrial applications. As recognized in the available literature, most studies aim to emphasize the effectiveness of the proposed control algorithms, but seldom discuss its practical realization for optimal system performance.

Since most low cost embedded system plat-forms use fixed point microprocessors as CPU, the main concern then comes from the fixed pointed arithmetical errors and in particular the instability occurred during real time implementation, together with an increased burden on streamlining the code and not sacrificing much performance. Therefore, it is better to consider these hardware constraints starting from the control design stage, so as to make appropriate trade-offs between feasibility, high performance control and robustness.

To fully exploit the potential and benefits of advanced controls for piezo-actuated systems using embedded controller, this study proposes a hybrid neural-repetitive control method and investigates its implementation issues on a FPGA based embedded system platform. In the following the applied embedded control platform is first illustrated. The design and realization issues of the hybrid control are then discussed. Finally, repetitive tracking

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experi-ments performed on a piezoelectric actuator sys-tem reveal the effectiveness of the proposed method and its feasibility using embedded hardware.

2 FPGA-Based Embedded Control Platform

This study applied an embedded and programmable controller CompactRIO from National Instruments to investigate the advantages and issues occurred in implementing advanced digital controls. To exploit the practical merits by using embedded hardware, a fast piezoelectric actuator control system is se-lected as the experimental apparatus for controller performance evaluation. As shown in Figure 1, the CompactRIO controller comprises four main parts, including a real-time module, a FPGA module, a NI 9215 A/D module and a NI 9263 D/A module. The real-time module is used to store data and communicate with the FPGA module, a reconfigurable FPGA based operating environment with a maximum processing rate up to 40 MHz. The control algorithm is calculated at the FPGA side using LabVIEW language. The control signal is sent to a piezo-driven actuator system (Piezomechanik Pst 150/5/20 VS10) and the sensor signal from a stain gauge amplifier is fed back to the FPGA module, constituting a feedback control system. Figure 2 shows the photograph of the experimental apparatus applied in this study.

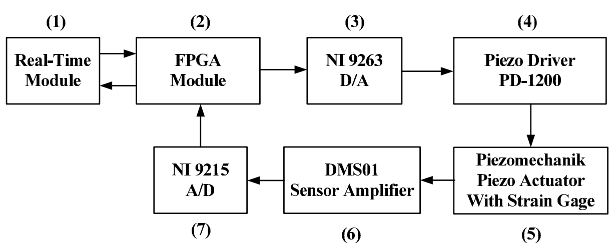

Fig. 1: Schematic diagram of an embedded control platform for a piezo-actuated system.

3 Adcanced Digital Control via Hybrid Neural-Repetitive Control

A great number of works has been conducted for precision tracking control of piezo-actuated systems. The main challenge here is achieving desired tracking performance subject to the dominant hysteresis effect and uncertain parameters change. As widely known, neural control is an effective method which can deal with nonlinear and uncertain systems. To attain high performance and robustness of piezo tracking control at the same time this study presents an advanced digital

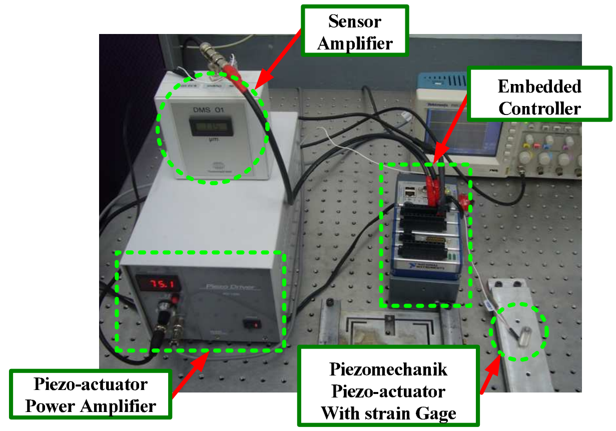

Fig. 2: Photograph of the experimental setup.

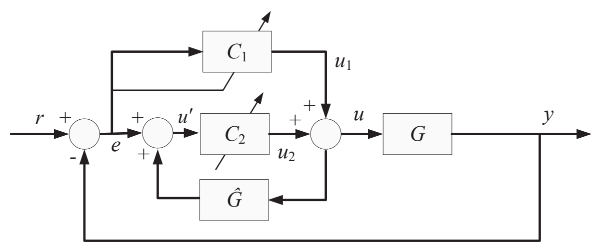

Fig. 3: Block diagram of the proposed advanced control for piezo tracking control.

control method im-plemented using a FPGA based embedded control platform. Besides the existing neural controllers, a repetitive controller is added to improve the periodic tracking control performance as explained in the following section.

3.1 Control Design

Figure 3 illustrates the control block diagram of the proposed hybrid neural-repetitive control for piezo tracking applications.

In Figure 3, C_1 and C_2 represent two different controllers with control inputs u_1 and u_2, respectively. $\hat{G}$ is the plant model of G, which can be obtained using standard system modeling and identification techniques. The transfer function from reference r to tracking error e is presented as follows:

$$e = \frac{1-\hat{G}C_2}{1+GC_1}r. \tag{1}$$

With the assumption that $\hat{G} \approx G$, the magnitude of the sensitivity function for reference tracking is further reduced by introducing this control architecture.

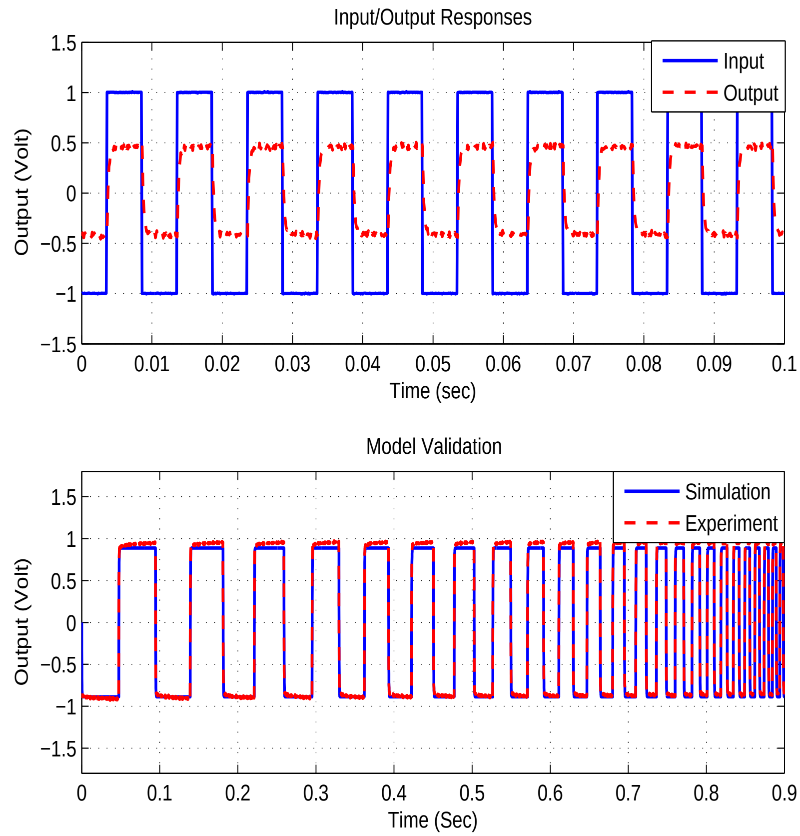

Fig. 4: System identification based on embedded control platform: top plot: injected input and output responses; bottom plot: model validation result.

In this paper, C_1 is selected as a radial basis function (RBF) based neural network adaptive controller. The control goal of this controller is to stabilize the system as a performance baseline. To further improve the control performance, another neural controller C_2 containing a repetitive controller for periodic errors cancel-lation is added. The design of C_2 is based on the technique mentioned in [16].

In this section we will illustrate how to construct a neural-repetitive controller using the idea of feedforward control with internal model constraints. Consider the case of using controller C_2 alone, equation (1) then becomes

$$e = (1 - \hat{G}C_2)r. \tag{2}$$

The original feedback control problem has been transformed to a feedforward control problem and the control goal here is to minimize the tracking error with a cost function $J = (1 - \hat{G}C_2)$. The simplest solution to this control problem is to find a stable plant inverse of $\hat{G}$ [17]. In practical applications we are interested in the case when the system input contains some specific internal models D, which is usually known a priori. For example, we may know the periodic components in the applied tracking profile for precise positioning applications. Now let

$$1 - \hat{G}C_2 = RD, \tag{3}$$

where R is a part of the controller C_2 and needs to be designed. The above equation is recognized as the famous "Bezout Identity"[18] with the assumption that $\hat{G}$ and D are coprime. This equation has infinite solutions and one way to represent these multiple solutions is using Youla parameterization technique [18]. Given a pair of nominal solution (R', C_2'), we can express the solutions of equation (3) as $R = R' - \hat{G}Q$ and $C_2 = C_2' + DQ$, where Q is a free design para-meter. Consider the performance index with 2-norm measure:

$$J = ||(R' - \hat{G}Q)D||_2. \tag{4}$$

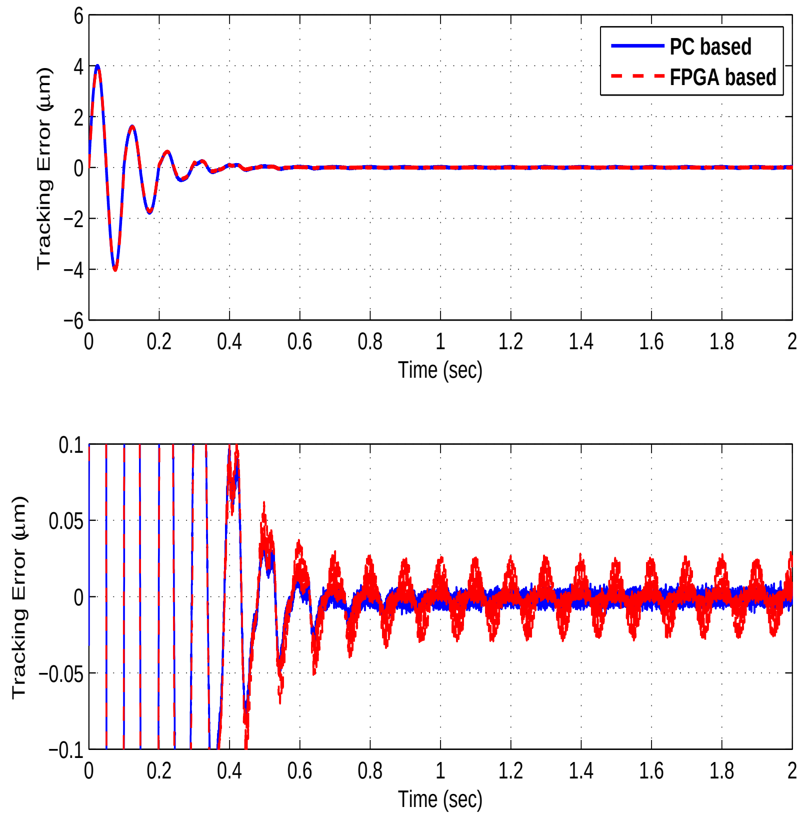

Fig. 5: Repetitive control tracking results: comparison of using PC based and FPGA based controllers.

Then the control goal of the neural controller C_2 is to minimize J and satisfy the deterministic constraint described by the internal model D simultaneously. The selection of the internal model depends on the input signals we are dealing with. In this work the input signal is a periodic one for tracking control, so D is chosen as $D = 1 - z^{-N}$, where N is the period of the deterministic periodic signal. With above assumptions, we can represent this constrained optimization problem as

$$\min_{\substack{Q \in RH^{\infty} \\ D = 1 - z^{-N}}} ||(R' - \hat{G}Q)D||_2, \tag{5}$$

where RH^{∞} is a set of stable rational transfer functions. To minimize J and update Q adaptively, a RBF neural network algorithm [19] is applied in this paper.

To solve the Bezout identity equation (3) and update the adaptive neural controller Q, this work adopted the method using a zero-phase-error-tracking type feedforward formula [17]. The procedure for obtaining this particular solution is briefly listed as follows.

Consider a single input, single output (SISO) plant model $\hat{G}$ and factorize $\hat{G}$ into two parts $\hat{G} = G_o G_i$, in which G_o is minimum phase and G_i is non-minimum phase, respectively. Suppose

$$\begin{aligned} \hat{G} &= \frac{B}{A} = \frac{B^+ B^-}{A} = G_i G_o, \\ G_0 &= \frac{B^+}{A}, \quad G_i = B^-, \end{aligned} \tag{6}$$

where A and B represent the denominator and numerator of $\hat{G}$, B^+ and B^- denote the stable and unstable parts of B, respectively. Substituting equation (6) into equation (3), one can obtain

$$\begin{aligned} RD + \tilde{C}_2 G_i &= 1 \\ \tilde{C}_2 &= C_2 G_o. \end{aligned} \tag{7}$$

From the plant inversion idea presented in [17] one solution pair (R', C_2') to solve equation (7) is given as follows:

$$\begin{aligned} R' &= \frac{1}{1-(1-\gamma G_i^* G_i) q z^{-N}} \\ \tilde{C}_2 &= \frac{\gamma G_i^* q z^{-N}}{1-(1-\gamma G_i^* G_i) q z^{-N}} \\ \tilde{C}_2' &= C_2' G_o^{-1}, \end{aligned} \tag{8}$$

where γ is a learning parameter for performance tuning, $G_i * (z^{-1}) = Gi(z)$, and $q(z, z^{-1})$ is a zero phase low pass filter to suppress the instability caused by the high gain feedback at undesired frequency ranges. This q filter is embedded within the internal model $D = 1 - q(z, z^{-1}) z^{-N}$. Although q is a discrete non-causal filter, the causality condition still holds in equation (8) because of the long term delay cascaded with q. For a detailed parameter analysis of the controller, one may refer to [16].

3.2 Implementation Issues

Just like many embedded controllers, CompactRIO is a fixed point based control platform which involves issues such as "quantization error" and "finite word length error" in real implementation. All these inevitable errors may deteriorate the control performance and even system stability if not carefully addressed. Therefore, saving as many logic gates in FPGA as possible to optimize the static and dynamic arithmetical range and avoid overflow, or equivalently "program optimiza-tion", is an important design step especially when using complicated servo control algorithms or high sampling rates for fast dynamic systems.

As mentioned in the previous section, this study applied an advanced control consisting of an adaptive neural controller and a repetitive controller. When using an embedded control platform such as CompactRIO, each control action needs extra design efforts for successful implementation. To make these ideas clear, some issues regarding the proposed controller implementation can be summarized as follows:

3.2.1 Model and controller order

If the control law is designed using a model based design method such as repetitive control, a low order plant model is preferred. High order mathematical models usually need high order controllers for successful control design. Reduction of controller order is one way to deal with this problem but may introduce more undesired errors. For this reason the model of the piezo-actuated system in this study is identified based on a system identification technique and fitted to a third order control system.

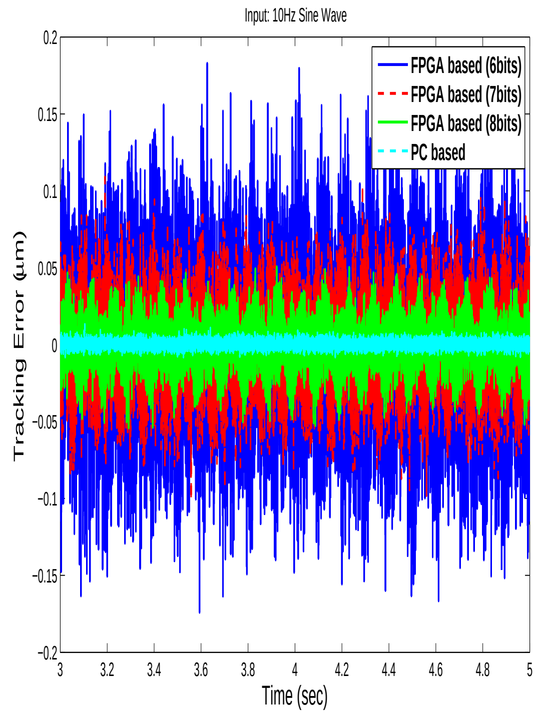

Fig. 6: Steady state tracking error of repetitive control by using an embedded control platform: finite word length effects.

3.2.2 Realization of the neural network controller

The neurons φ applied in the neural controller are Gaussian functions and can be represented as:

$$\varphi(||x-c||) = exp\left[-\frac{||x-c||^2}{2\sigma^2}\right], \tag{9}$$

where c and σ denote the center and standard deviation of the Gaussian function, respectively. It is not difficult to implement the above nonlinear function and achieve desired precision if using a floating point based microprocessor. For fixed point based microprocessors the approximation of this exponential function can be made by using a finite Taylor series expansion:

$$exp(x) = \sum_{k=0}^{N} \frac{x^k}{k!}. \tag{10}$$

To reduce the computational burden this study applied a second order $(N = 2)$ approximation to implement the neurons in the neural controller. Moreover, the applied RBF network consists of an input layer, one hidden layer and output. The hidden layer has two neurons, meaning only two sets of neuron parameters need to be determined. For simplicity, the values of c and σ of the radial function φ are fixed.

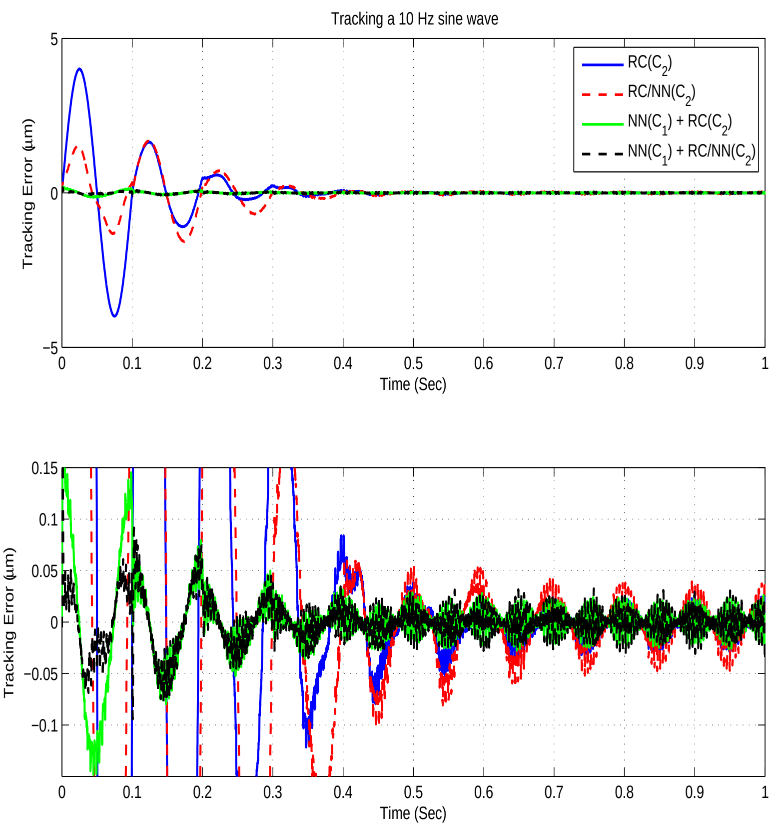

Fig. 8: Experimental results of tracking a 4 μm, 10 Hz sinusoidal input; top plot: time response in 1 second; bottom plot: zoom in; blue line: RC (C_2); red line: RC/NN (C_2); green line: NN (C_1) + RC (C_2); black line: NN (C_1) + RC/NN (C_2).

3.2.3 Realization of the repetitive controller

From the perspective of signal processing, the repetitive control shown in equation (8) basically comprises three components: Finite Impulse Response (FIR) filter, Infinite Impulse Response (IIR) filter, and long term time delay. Because of the constraints coming from fixed point operations and limited memories, it is crucial to streamline the FPGA code and maintain acceptable performance with minimal errors caused by the embedded hardware. For example, using a direct form II realization of second-order IIR filter may reduce the number of used registers, but on the other hand it also requires more dynamic arithmetical range and memory space comparing to a direct form I realization method. In light of this, a simulation analysis is performed to determine the optimal realization structures before implementation.

4 Implementation on a Piezo-Actuated System

To demonstrate the effectiveness and investigate the implementation issues of the proposed advanced control on the embedded control platform, trajectory tracking experiments were performed by giving a 4μm, 10 Hz sinusoidal reference input to the piezo-actuated system as described in Section 2. For a high bandwidth piezoelectric actuator system, the sampling rate was selected as 10 kHz to avoid possible “inter-sample” errors.

4.1 System Identification

Because the repetitive control is a model based design method, a mathematical model is still required for the control design. To this end this study applied a time domain system identification (ID) method and injected a series of square wave to the piezo actuator system as input. Figure 4 shows the system ID result based on the embedded controller CompactRIO. After filtering out the

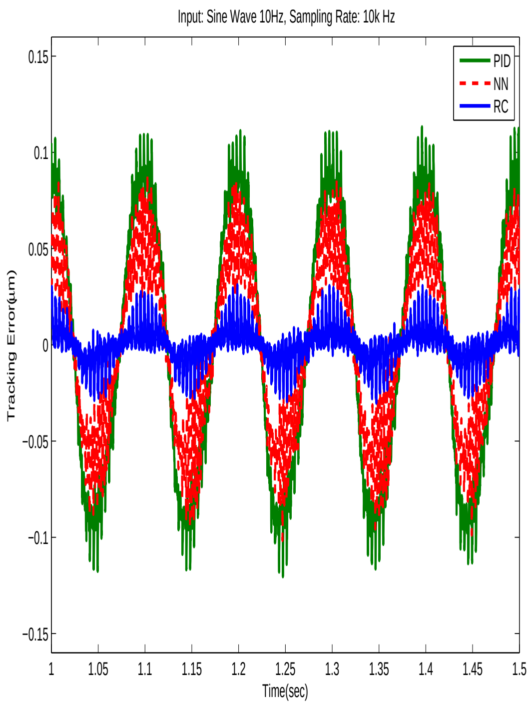

Fig. 7: Steady state tracking error comparison: green line: PID; blue line: NN; red line: RC.

undesired noises and fixed point errors for the output signal, a third order discrete time model at 10 kHz sampling is obtained by using the system ID toolbox 'ident' in Matlab and can be represented as:

$$G(z) = \frac{0.1696z^2 - 0.04588z}{z^3 - 0.8602z^2 + 0.1239z + 0.01492}. \quad (11)$$

A different input signal, frequency varying square wave, was also injected to the control system to verify the accuracy of the model, as shown in figure 4.

4.2 Tracking Results

Figure 5 shows the tracking error results by using repetitive control (RC) alone (i.e., disabling C_1 and the neural controller part in C_2). To highlight the effects of fixed point embedded controller, the result based on a floating point controller is also plotted for illustration. As can be seen, using a floating point based control platform assures the asymptotic error property because of the use of the repetitive controller. However, undesired ripple errors occur at the steady state if the control is implemented using a fixed point microcontroller. For comparison purpose the results using three different resolution based arithmetic operations are also shown in Figure 6. It is clear that the finite word length errors become more significant with a decreasing precision in the embedded control system. The result presented indicates that there exists an inherited conflict between hardware resources and performance in particular when implementing on a fixed point embedded controller.

Next, we present the experimental results of using neural controller C_1 by comparing with two other controllers, PID control and repetitive control. Note that so far the hybrid control mechanism is still not activated. As shown in Figure 7, the neural controller, although only with two neurons in the implementation, still achieves better performance than the fine-tuned PID controller. The obvious periodic errors shown in the plot thus motivate the extra use of repetitive control for better performance over neural network control alone.

Figure 8 represents the tracking results by using our proposed hybrid neural-repetitive control based on an embedded control platform. It is clear from the top subplot that a large transient error occurs in the first period cycles. Adding a neural controller C_1 considerably reduces the transient error down to a $\pm\, 0.15\mu$m range. In particular, activating all the control actions in C_2 further improves the transient performance, as indicated in the bottom subplot. Although applying more control actions seems giving the best tracking performance, it is noticed that accumulated fixed point errors also lead to increased steady state errors (blue line v.s. black line).

5 Conclusion

In this paper, we present an advanced digital control method which combines neural control with repetitive control for tracking control of piezo-actuated systems. The developed control algorithm was implemented using a FPGA based embedded control platform. Experimental results on periodic tracking control of a piezo-actuated system demonstrate the effectiveness of the proposed method. From the results obtained, it is suggested to take into account the issues of error reduction, computational burden, and programming efforts for best system performance when using embedded hardware for advanced controls implementation.

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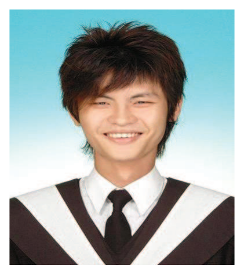

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