Real-Time Adaptive Feedforward Zero Phase Error Tracking Control For XY Table Minimum Phase And Non-Minimum Phase Systems

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ABSTRACT

This paper presents the realization of feedforward Zero Phase Error Tracking Control (ZPETC) for real-time XY table application. Using different sampling times in system identification technique, a minimum and non-minimum phase mathematical models can be obtained from input-output experimental data to represent the true plant of the XY table. These two models are used to test the effectiveness of designed controllers. In this paper, two types of feedforward ZPETC controller are developed. Conventional ZPETC introduced by Tomizuka is tested and then the technique is modified by eliminating the factorization of zero polynomials. This is done by changing the gain compensation filter by Finite Impulse Response (FIR) filter. The gain adaptation mechanism is done using Recursive Least Square (RLS) algorithm. The contour error is used as indicator for tracking performance effectiveness. The experimental results show that the modified controller can effectively enhance the tracking performance of the system and provide superior two dimensional contour plots for the XY table for both types of system.

Keywords— Feedforward ZPETC; Real-Time Control; System Identification; Tracking Control; XY Table

I. INTRODUCTION

The XY table requires high accuracy and precision. This is because it is normally applied in electronic manufacturing, laser cutting, wire cutting and CNC machining. In order to achieve high precision positioning tracking system, the tracking error for each axis must be minimal. This would lead to great challenge to the researchers. The tracking controls for the individual axis can indirectly reduce the contour error [1]. According to Wang et al. [2] the x-y plane contour accuracy is dominated by position and tracking error of each axis. Satisfying the accuracy requirement is very important particularly for direct input used as reference for a servo motor. This kind of system usually represented by a non-minimum phase (NMP) system due to fast sampling-time used during modeling to avoid the lost of plant dynamic characteristics. A non-minimum phase system will have internal stability problem when the inverse closed-loop transfer function is used directly as feed-forward controller. A discrete-time non-minimum phase model posses one or more zeros outside the unit circle. However, using slow sampling-time during data acquisition process, the minimum phase plant model can be acquired.

The feed-forward Zero Phase Error Tracking Control introduced by Tomizuka [3] is effective and has been used widely in solving unstable system as in [4]–[7]. This technique is suitable only for low frequency. Many researchers have modified this technique to achieve better control performance [8] – [11].

The main objective in feedforward ZPETC is to find the optimum gain filter so that the overall gain is close to unity. To avoid the unwanted phase error, Yeh and Hsu [12], Mustafa [13] and Adnan *et al.* [14] used ZPETC without factorization of zeros polynomial. In this method, gain filter is proposed as FIR filter. The filter coefficient can be solved using comparing coefficient method as presented in [15] and Laurent series expansion method [16]. To obtain the optimum coefficients values, adaptive control technique proposed by Adnan *et al.* [14] is considered. Further improvement is presented in this paper by adding model reference as the excitation signal to find the optimum value of the coefficients.

The plant mathematical models were identified from ac servo XY table. To avoid the mechanical complexity and application of physic laws, system identification technique is used. This technique used input/output data performed in time domain to derive the model transfer function. In this part, sampling-time is varied from 45ms to 60ms to change the zero location from outside to inside the unit circle. For the purpose of results analysis, contour error is measured for each testing. Contour error is described as the minimum distance from point to point to a prescribed contour. For a constant radius circular contour, the error calculation is simple [17].

The rest of the paper is organized as follows: Section II discussed on XY table plant setup and mathematical modeling; Section III discussed the design of Adaptive feed-forward ZPETC; Section IV is on results and discussion; and finally, Section V is the concluding remark.

II. Hardware Setup and Model Identification

A. Hardware Setup

The XY table used in this paper consists of a servomotor connected to a roller shaft for each axis, two servo drivers, two displacement precision sensors, Advantech PCI 1240 motion card, Advantech PCI 1716 data acquisition (DAQ) card and a host PC set. The displacement sensor resolution is 1 μm. The minimum movement of the motor is 1μm. The plant schematic diagram for the whole system is given in Fig. 1. Microsoft Visual C++ 6.0 programming language was used for system control and interfacing. For model identification, Matlab system identification toolbox was used. For data and results analysis, Matlab software was also utilized.

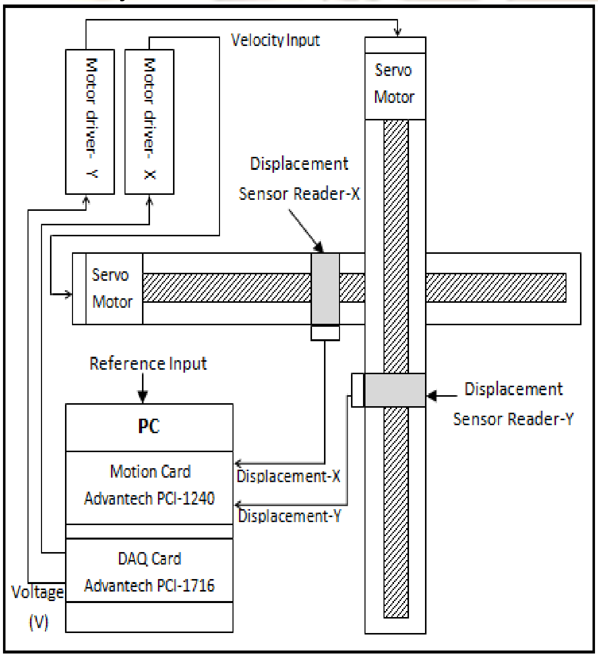


Fig. 1 Plant schematic diagram

The control algorithm and system interfacing is embedded in a developed C++ program. The reference input is given in the form of a mathematical equation in the program. The program is linked to DAQ and motion card for the input/output interfacing. The controlled signal will generate output voltage from DAQ card to the motor driver to control the servomotor. To have a precise measurement, the output from a precision displacement sensor is acquired instead of the displacement output from the servomotor encoder. Motion card retrieves data and sends them to the program. The constraint of the system is that the controlled signal voltage is saturated at ±10V. This will limit the speed of the motor. The XY table real plant picture is shown in Fig. 2.

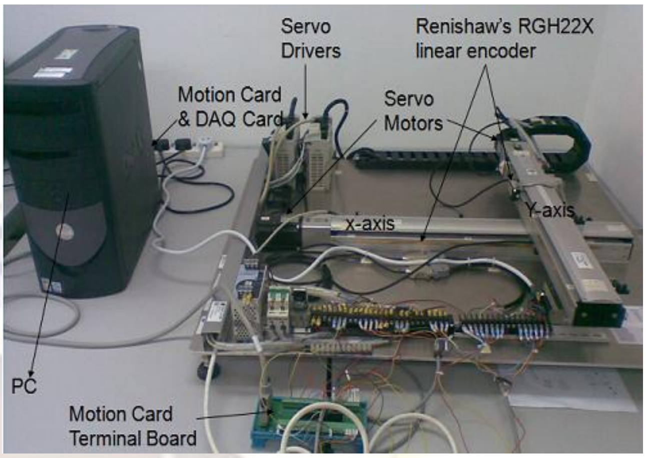


Fig. 2 XY table

B. Model Identification

To acquire the system mathematical model transfer functions, system identification technique was applied. This technique models a system based on the input-output data. Data collection for input-output open-loop test of the plant was done using developed Visual C++ console programming and data acquisition were done through Advantech PCI-1716 interface card and Advantech motion card. The input signal for both axes was generated using three different frequencies that based on Equation (1).

$$u(k) = \sum_{i=1}^{p} a_i \cos \omega_i t_s k \qquad (1)$$

a_i : amplitude
ω_i : frequency (rad)
t_s : sampling time (sec)
k: integer

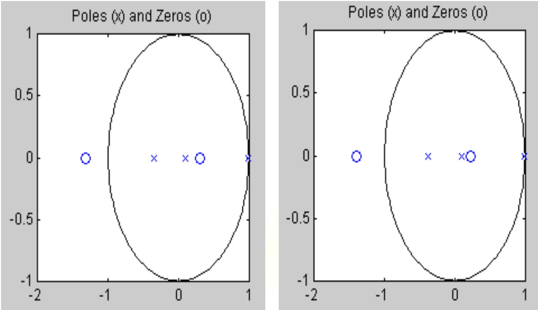
For model identification, a third-order ARX331 model was selected to represent the nearest model of true plant. This selection produced satisfactory third-order transfer function. To test the performance of the controller, a minimum and non-minimum phase models are used. The models were obtained from Open-loop input/output data response collection using sampling-time of 45ms and 60ms. Reducing the sampling time will make the zero be placed outside the unit circle. Open-loop input/output data response collection for the x and y axis was done simultaneously to achieve a perfect XY table system and to avoid dynamic miss-matching between X axis and Y axis problem [18].

The obtained non-minimum phase model using 45ms sampling-time is given by Equation (2) for x axis and Equation (3) for y axis.

$$\frac{B_o(z^{-1})}{A_o(z^{-1})} = \frac{1.132z^{-1} + 1.1614z^{-2} - 0.4516z^{-3}}{1 - 0.7498z^{-1} - 0.2873z^{-2} + 0.03625z^{-3}} \quad (2)$$

$$\frac{B_o(z^{-1})}{A_o(z^{-1})} = \frac{0.996z^{-1} + 1.17z^{-2} - 0.3076z^{-3}}{1 - 0.7298z^{-1} - 0.3098z^{-2} + 0.03974z^{-3}} \quad (3)$$

The pole and zero plots are shown in Fig. 3 below.



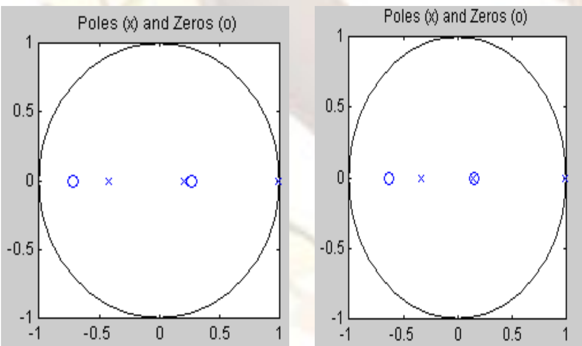
X-Axis Y-Axis

Fig 3. Zero-pole plot for x and y axis for 45ms sampling time

For the minimum phase model using 60ms sampling time, the best fits for x-axis is 93.62% and for y-axis is 96.28%. The plant x-axis mathematical model in the form of discrete-time open-loop transfer function is given by Equation (4) and for y axis is by Equation (5). The pole and zero plots of the minimum phase system are shown in Fig. 4.

$$\frac{B_o(z^{-1})}{A_o(z^{-1})} = \frac{1.729z^{-1} + 0.7567z^{-2} - 0.3407z^{-3}}{1 - 0.7869z^{-1} - 0.2983z^{-2} + 0.08543z^{-3}} \quad (4)$$

$$\frac{B_o(z^{-1})}{A_o(z^{-1})} = \frac{1.584z^{-1} + 0.7458z^{-2} - 0.1583z^{-3}}{1 - 0.8051z^{-1} - 0.2438z^{-2} + 0.04917z^{-3}} \quad (5)$$



X-Axis Y-Axis

Fig.4 Zero-pole plot for x and y axis for 60ms sampling time

III. Controller Design

This section describes the development and implementation of the controller design. Feedback and feed-forward ZPETC controller are applied to the system. Feedback control has always come with the feed-forward control for two degree of freedom (DOF) control. The control system block diagram is given in Fig. 5.

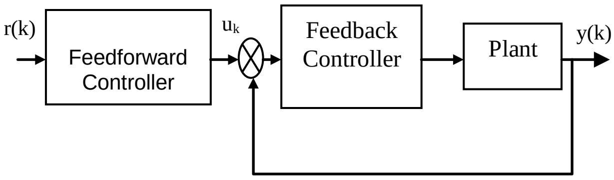


Fig.5 Control system block diagram

For the feedback control, pole- placement method is applied. The feedback control block diagram is illustrated in Fig.5. The pole-placement controller enables all closed-loop poles of the system to be placed at desired location. This will produce stable output performance.

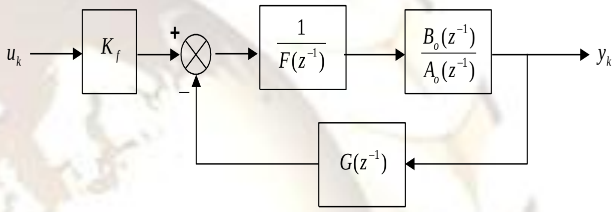


Fig. 6 Pole placement feedback control system block diagram

Generally, for the feedback control, we need to know the poles location. A pole position which is inside the unity circle is considered for the controller. Other poles cancelled each others. The range of considered pole-placement controller is between 0 to 1. For slow response, pole position is set large and for fast response it is set small. Details for pole placement feedback control and how to find equation F (z^{-1}) and G (z^{-1}) can be obtained from [16].

For the feedforward ZPETC, let the closed-loop transfer function of the feedback system be presented by:

$$G_{cl}(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{z^{-d}B_c(z^{-1})}{A_c(z^{-1})} \quad (6)$$

$$A_c = 1 + a_1 z^{-1} + a_2 z^{-2} + ... + a_{n_a} z^{-n_a}$$

$$B_c(z^{-1}) = b_o + b_1 z^{-1} + b_2 z^{-2} + ... + b_{n_a} z^{-n_b}$$

d = *time delay*

The function B_c (z^{-1}) can be factorized into minimum and non-minimum phase factors by:

$$B_c(z^{-1}) = B_c^{+}(z^{-1})\ B_c^{-}(z^{-1})$$

The structure of ZPETC is proposed by Tomizuka [3] is presented by the following block diagram:

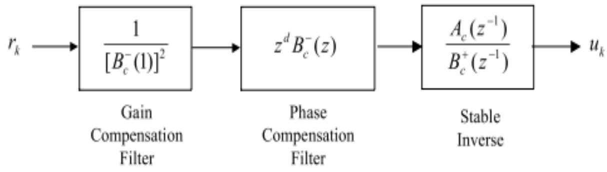


Fig.6 ZPETC structure block diagram

Based on [13] the ZPETC structure in Fig.6 has been modified by a new structure without factorization of zeros polynomial. The control structure of ZPECT without factorization of zeros is shown in Figure 7.

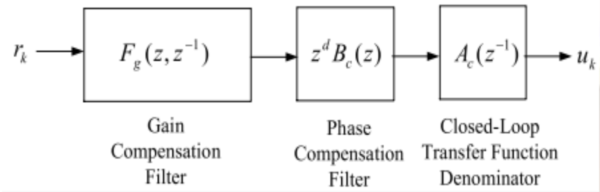


Fig. 7 ZPETC without factorization of zeros polynomial

In this paper, the same approach as applied in [12], [13] and [14] is followed to avoid phase error. Finite Impulse Response (FIR) symmetry filter is used as the gain filter. The filter can be represented by Equation (7).

$$F_g(z\ z^{-1}) = \sum_{k=0}^{n\alpha} \alpha_k \left(z^k + z^{-k}\right) \qquad (7)$$

The cost function to represent the error between desired and actual frequency response is given by Equation (8).

$$J(\alpha_i) = \left\| 1 - B_c\left(z^{-1}\right)B_c(z)\sum_{k=0}^{n_\alpha} \alpha_k \left(z^k + z^{-k}\right) \right\|_{l_2} \qquad (8)$$

The objective here is to find a set of α_k so that can minimized the cost function. By minimizing the cost function of Equation (8) close to zero, the equation can be transformed to be:

$$B_c\left(z^{-1}\right)B_c(z)\sum_{k=0}^{n_\alpha} \alpha_k \left(z^k + z^{-k}\right) = 1 \qquad (9)$$

The optimal set of α_k is estimated using the recursive least square (RLS) parameter estimation algorithm. This system can be represented by the block diagram given in Fig. 8.

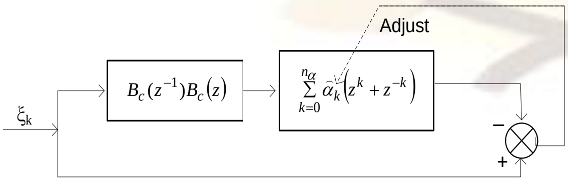


Fig. 8 Adaptive ZPETC gain filter

Based on [14], in ensuring the generated signal ξ will always persistently exciting, a low level noise signal which its frequency spectrums close to the reference signal frequency spectrums is superimposed to the reference signal. The noise addition will not affect the system as it will not pass through the tracking system. It is used only for parameter estimation. To improve this parameter estimation part, this paper proposes model reference signal to be used instead of reference signal. The complete block diagram of the system utilizing this method is given in Fig. 9.

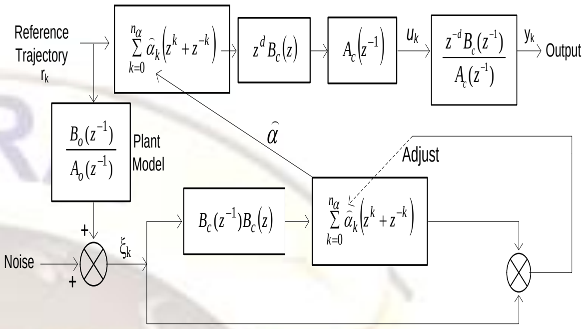


Fig. 9 Feedforward ZPETC without factorization of zeros

The implementation of the proposed structure was done on real-time experiment using Visual C++ console programming. The forgetting factor used was 0.95.

IV. RESULT AND DISCUSSION

The results for real-time experiments are analyzed to show the effectiveness of the proposed controller for both minimum and non-minimum phase systems. The reference input, r_k for x-axis is a sine function and for y-axis, a cosine function is used to produce circular contour in x-y plane. The equations of the input signal are given by Equation (10) for x-axis and Equation (11) for y-axis.

$r_k = 40\sin(0.015t)$ (10)

$r_k = 40\cos(0.015t)$ (11)

The real-time experiments were initially done with feedforward ZPETC controller with factorization of zeros. The experiments were conducted using same inputs to the two types of model namely, minimum phase and non-minimum phase as stated in Section II. This is to test the effectiveness of the controller for different types of system model.The result for non-minimum phase system is plotted in Fig.10 whereas the result for minimum phase system is plotted in Fig.11.

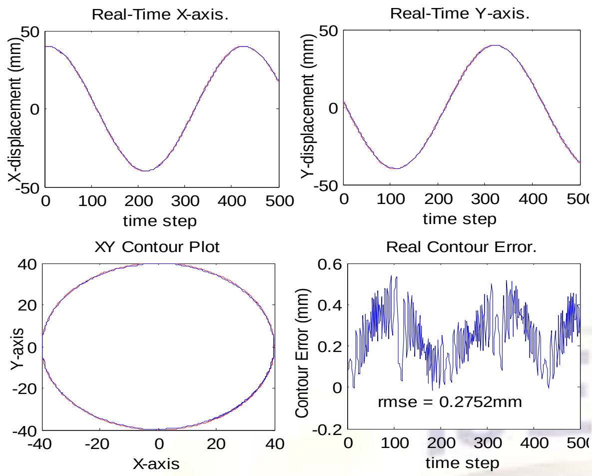


Fig. 10 Experimental results using ZPETC for non-minimum phase model

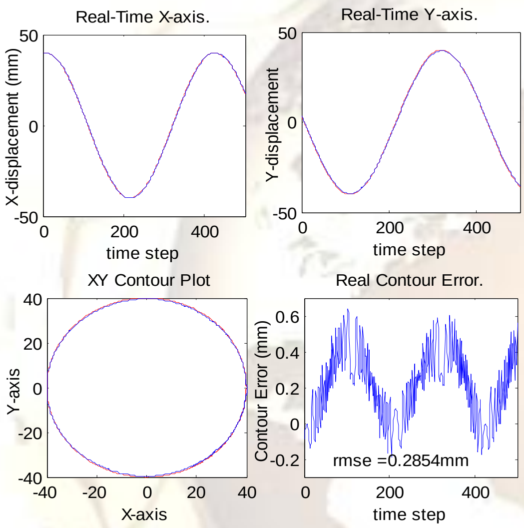


Fig. 11 Experimental results using ZPETC for minimum phase model

From the contour error plot in Fig. 10 and Fig.11, it can be said that the error variation for minimum phase model is very sharp and higher compared to the non-minimum phase model. As for the non-minimum phase system, the sharp angle of the contour error is compensated and thus it produces better performance.

For the adaptive ZPETC, the experiments were done by varying the filter order. The gain compensation filter order, n_α used in the experiments were 2,5,10 and 15. Since the contour error differences between the filter order is so small, only one plot for each model are presented. Presented plots are for 15th order filter and are given in Fig. 12 and Fig. 13.

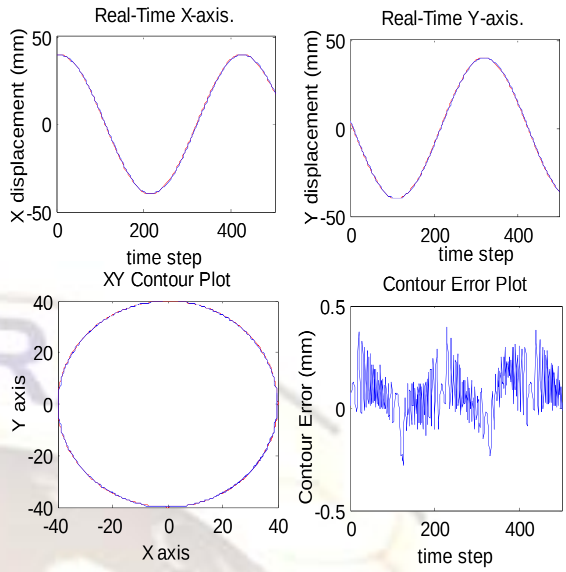


Fig. 12 Experimental results using 15th order filter for non-minimum phase model

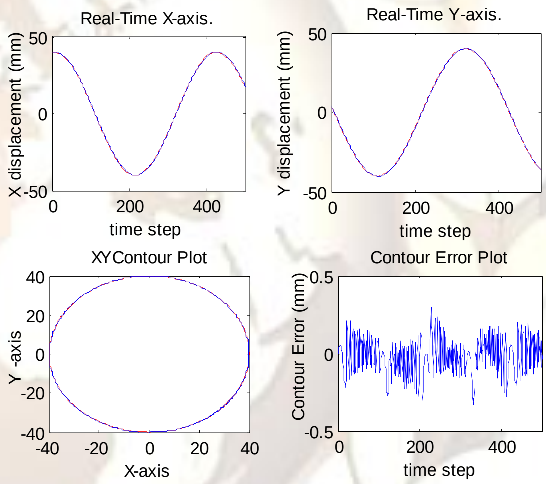


Fig. 13 Experimental result using 15th order filter for minimum phase model

From Fig. 12 and Fig. 13, the real-time experimental results for both models show impressive tracking performance achieved using the developed adaptive ZPETC controllers. There is no sharp angle variation in the contour error plots. To acquire the contour error, many approaches can be used as stated by Yang et. al [17]. As the reference contour input used is a circle with constant radius, simple equation as in equation (12) is applied. The contour error is plotted for every trials.

$$Contour \quad error = Radius - \sqrt{x^2 + y^2} \tag{12}$$

The contour error plots obviously show significant differences. The contour error variation using adaptive ZPETC is small compared to the conventional ZPETC for both types of models. The root mean squared of the contour errors using equation (13) are summarized in Table I.

$$Root\ Mean\ Square\ Error = \frac{\sum_{i}^{N}(Contour\ Error)^2}{N} \quad (13)$$

TABLE I. CONTOUR RMSE SUMMARY FOR ADAPTIVE FEEDFORWARD ZPETC

Controller Type	Root Mean Squared Error (mm)	
	Non-Minimum Phase Model	Minimum Phase Model
ZPETC with factorization of zeros	0.2753	0.2854
Adaptive ZPETC Filter order = 2	0.1399	0.1136
Adaptive ZPETC Filter order = 5	0.1389	0.1125
Adaptive ZPETC Filter order = 10	0.1379	0.1115
Adaptive ZPETC Filter order = 15	0.1377	0.1111

From the summarized contour root mean squared error given in Table I, the conventional ZPETC can give better control for non-minimum phase system. Besides that, by applying adaptive ZPETC, the error is very small for both types of systems. The minimum phase tracking performance shows better results due to zero location away from unity circle. This imply that the proposed adaptive ZPETC controller can be applied to both types of system and much better as compared to Tomizuka [3] ZPETC. By increasing the filter order, the contour error is reduced about 1 µm. These results show that the proposed adaptive ZPETC controller can significantly control the XY table irrespective of system types.

Besides that, better tracking performance can also be achieved by raising the filter order so that the controller will have more degree of freedom to approximate the overall transfer function to unity. Good tracking for each axis will indirectly improve the contour performance. Simulation results on the effect of filter order can be referred to [19]. However, for real-time application, the voltage saturation has limited the tracking performance.

V. CONCLUSION

Conventional ZPETC controller and adaptive ZPETC without factorization of zeros were developed and implemented to XY table by real-time experiment. The performances of the controllers over the minimum and non-minimum phase system plant models were analyzed. The proposed adaptive ZPETC controller shows that it can provide impressive tracking performance for both minimum phase and non-minimum phase systems. Reducing the tracking error will indirectly lead to better contour. In addition, for the adaptive ZPETC, the contour errors for both model types are very small. The minimum phase system gives slightly better performance compared to non-minimum phase system due to zero distance from the unity circle. While for the conventional ZPETC, it can control non-minimum phase system much better then minimum phase system.

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