EVALUATION OF SERVO-CONTROLLERS FOR MACHINE TOOLS

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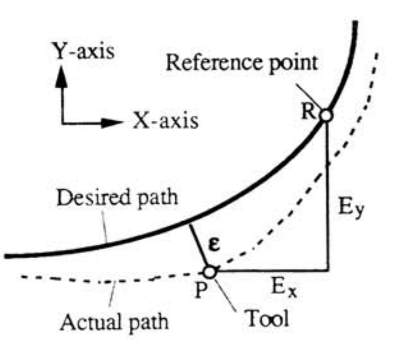
ABSTRACT

To achieve the high precision required in future contouring machining applications, accurate servo-controllers are needed. This paper summarizes existing servo-controllers for contouring applications and presents an evaluation of three basic types of controllers: feedback controllers, feedforward controllers, and cross-coupling controllers. The evaluation of servo-controllers includes: (1) their abilities in eliminating different error sources, and (2) their practical limitations in machine-tool control. The evaluation is supported by simulation and experimental results.

1 INTRODUCTION

There are two types of CNC systems: (1) point-to-point (PTP), and (2) contouring (or continuous-path). For PTP systems, a good axial positioning accuracy at the target points is required, and in general, a conventional P controller can satisfy this requirement [4,6]. However, a conventional P controller cannot completely eliminate the contour errors in machining contouring systems [5,6,11]. The contour error in machining a desired contour on a two-axis system is shown in Figure 1. We should emphasize that the contour error (ε), rather than the axial positioning error, is the prime concern, although the latter is usually given as the specification of CNC systems. Reduction of contour errors can be performed by three basic approaches: (1) applying sophisticated axial controllers, (2) adding feedforward controllers, and (3) using a cross-coupling controller.



ε: Contour error　　R: Reference position
E_x, E_y: Axial errors　　P: Actual tool position

Figure 1: Contour error in machining a contour.

In the first approach, more comprehensive controllers than P-controller are utilized (e.g., PID controller, state-feedback controller, etc.) [12,13]. The second approach is based on adding feedforward controller (e.g., ZPETC) to compensate for the axial position errors [3,7,14,15]. The above two approaches intend to *reduce the axial tracking errors*, and thereby reduce the resultant contour error.

In contrast, the philosophy of the cross-coupling control method [1,2,5,8-10] is that the *elimination of the contour error* is the controller objective, rather than the reduction of the individual axial errors. Therefore, the cross-coupling concept calls for the construction of a contour-error model in real time and utilizing it in the determination of a control law that reduces (or eliminates) the contour error.

This paper discusses the three basic types of servo-controllers and presents a comparison of them. The evaluation of servo-controllers includes: (1) their abilities in minimizing or eliminating different error sources, and (2) their limitations in machine tool control applications. The evaluation is supported by simulation and experimental results.

2 ERROR SOURCES

Contour error sources in machining may be classified into three categories: (1) mechanical hardware deficiencies (e.g., backlash, unstraightness of the table, etc), (2) cutting process effects (e.g., tool deflection, tool wear, etc), and (3) controller and drive dynamics. The total dimensional error is combination of all errors from the above sources. The first and second sets of error sources can be reduced by improving the mechanical hardware or utilizing compensation techniques. The third set of error sources, however, can be eliminated or reduced by improving the servo-control algorithms, and is the main concern of this paper. The contour error sources which are caused by the controller, drive dynamics, and external disturbances, can be further classified into three categories: (1) mismatch in axial-loop parameters, (2) external disturbances, and (3) the contour shape in nonlinear trajectories and corners.

A mismatch in axial-loop parameters causes contour errors. For example, in tracking a linear path, when using P controllers, a mismatch in the open-loop gains causes a steady-state contour error [5]

$$\varepsilon_{ss} = (\frac{f_x f_y}{f}) (\frac{K_y - K_x}{K_x K_y}) \quad (1)$$

where K_x and K_y are the open-loop gains of the X- and Y-axis; f_x and f_y are the required velocities along the X- and Y-axis; and f $(= \sqrt{f_x^2 + f_y^2})$ is the required feedrate (i.e., velocity) along the linear path.

The load disturbances include the cutting forces (not considered in this paper) and the friction of the machine guides. The latter is modeled as a step disturbance that its direction is always opposite to the motion.

When producing nonlinear contours, the inputs to the control loops are also nonlinear, and consequently, may cause contour errors. For example, for tracking a circle in a matched system, the steady-state contour (or radial) error can be described by the following equation [11]:

$$\frac{\varepsilon_{ss}}{\rho} = 1 - \frac{1}{\sqrt{1 + (2\zeta\omega/\omega_n)^2 - 2(\omega/\omega_n)^2 + (\omega/\omega)_n^4}} \quad (2)$$

where ρ is the radius of the circle, ζ and ω_n are the control loop damping factor and natural frequency, respectively, and $\omega = \rho f$, where f = feedrate.

3 FEEDBACK CONTROLLERS

The term "feedback controller" here means a controller that uses only basic feedback principles. In CNC these controllers may be classified into three basic classes: P, PID, and state-feedback controllers.

For conventional feedrates (e.g., 0.25 m/min = 10 ipm) and small disturbance loads, the P controller gives reasonable contour errors (e.g., 0.01 mm), and the dominate sources for dimensional errors on the parts are others than the servo errors (e.g., machine geometry, machine temperature, and tool deflection).

PID controllers produce smaller contour errors than P controllers. The two main problems with PID controllers in contouring applications are (1) poor tracking of corners and nonlinear contours, and (2) significant overshoots. Implementation of a PID controller requires careful preprograming of acceleration and deceleration periods, whereas they are not needed with P controllers.

The most common measurable states in CNC are the position and the velocity. The actual position is measured by incremental encoder and associated counter, and the velocity may be measured either by a tachometer [6] or by differentiating the measured position [12,13]. If the feedback states are the position and the velocity, the state-feedback controller is in fact a PD-controller. The major drawback of the state-feedback controller is its low effectiveness in eliminating the steady-state errors, as in the case of linear cuts, and rejecting external disturbances.

4 FEEDFORWARD CONTROLLERS

To decrease the tracking errors, feedforward controllers might be added to the control loops. We discuss below two basic types and improved feedforward controllers.

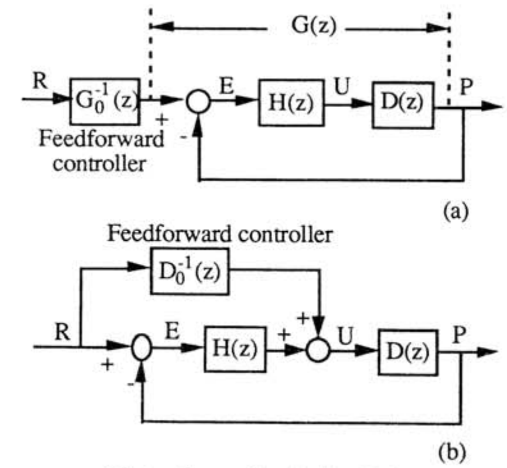
4.1 Basic Feedforward Controllers

There are two principle types of feedforward controllers, that are shown in Figure 2. The principle of the design in Figure 2a [3,14,15] is simple: Implement in the control computer a transfer function $G_0^{-1}(z)$ that is the exact inverse of the one of the real control loop, G(z), i.e., $G_0^{-1}(z)G(z) = 1$, and then the actual position becomes equal to the required position.

The design in Figure 2b has the same objective [7]. If we implement an inverse transfer function of the drive unit in the feedforward controller block, as shown in Figure 2b, we obtain the following closed-loop equation:

$$\frac{P}{R}(z) = \frac{D_0^{-1}(z)D(z) + H(z)D(z)}{1 + H(z)D(z)} = 1 \quad (3)$$

where H(z) and D(z) represent the transfer functions of the software controller and the drive unit, respectively. If $D_0(z) = D(z)$, the overall relation between the required position and the actual position becomes 1:1.



H(z) = Controller, D(z) = Drive unit

Figure 2: Two principle types of feedforward controllers.

4.2 Zero Phase Error Tracking Controller

The concept of the first type of feedforward controller is based on pole/zero cancellation, i.e., $G_0^{-1}(z)G(z) = 1$. However, if $G_0^{-1}(z)$ includes unstable poles, it cannot be implemented as a feedforward controller, and therefore must be modified. Tomizuka developed [14] a zero phase error tracking controller (ZPETC) that can be implemented even when there are unstable zeros in the control loops.

The major drawback of the ZPETC method is that it requires precise knowledge of the dynamic behavior of the axial drive system. However, there might be a difference between the real drive system and the model used in the computer (i.e., modeling error), and therefore an additional error source is introduced to the controlled system. Another drawback is that the inverse transfer function in the feedforward controller will cause large control signals. These signals, in practice, will be limited by the permissible maximum output of the digital-to-analog converter and the maximum voltage of the motor, and therefore the performance of the controlled system is degraded.

5 CROSS-COUPLING CONTROLLER (CCC)

The cross-coupling control architecture was first proposed by Koren [5]. The main idea of cross-coupling control is to build in real time a contour error model based on the feedback information from all the axes as well as the interpolator, to find an optimal compensating law, and then to feed back correction signals to the individual axes. The cross-coupling controller includes two major parts: (1) the contour error model, and (2) a control law. Consequently, the differences between the various CCCs that were proposed by many other researchers, who followed the original work, are in the contour error model or in the control law [1,2,8-10], but all of them are based on the original concept in [5].

A recent version of CCC, the variable-gain cross-coupling controller, proposed by Koren and Lo [8], demonstrated excellent tracking ability on experimental system and its block diagram is shown in Figure 3. The principle of the CCC is to calculate in real time the real contour error ε, feed it into a PID control law W(z), and then add the resultant signals to each axis with appropriate signs. For a nonlinear contour, the gains C_x and C_y are nonlinear and time-dependent, and are calculated at each sampling period (10 ms on our system).

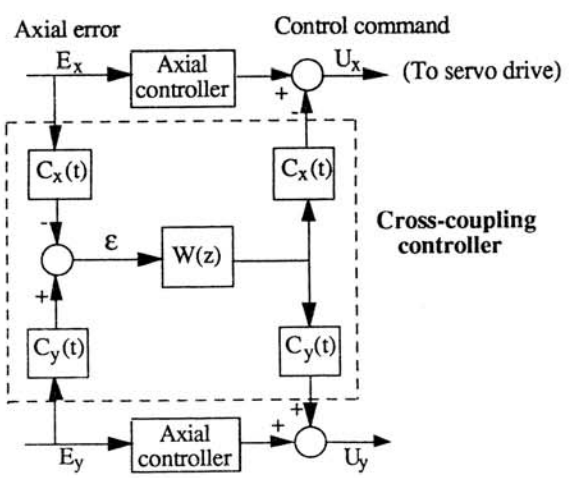


Figure 3: The variable-gain cross-coupling controller.

6 SIMULATIONS AND EXPERIMENTS

Three basic servo-controllers are analyzed in the following simulations and experiments.

(1) Feedback controllers: P controller and PID controller
(2) Feedforward controllers: ZPETC
(3) Cross-coupling controller: variable-gain CCC.

6.1 Simulation Comparison

Circular contours were simulated to analyze the controllers' ability to reject different error sources. As was stated above, contour errors are caused by three factors: (1) trajectory tracking disability, (2) axis mismatch, and (3) external disturbances. In addition, feedforward controllers have modeling errors and saturation errors.

Tracking and Mismatch. If the disturbances are negligible, the contour error is caused by trajectory tracking deficiency and the mismatch in axial parameters. Under these conditions, a circular contour was simulated for different servo-controllers and the results are shown in Figure 4. The simulation results show that (1) the PID controller results in poor trajectory tracking (especially for a high angular speed and small radius of curvature), (2) the ZPETC can achieve the best tracking performance if there is no modeling error nor disturbances, and (3) the CCC provides a much better tracking ability, compared to P and PID controllers.

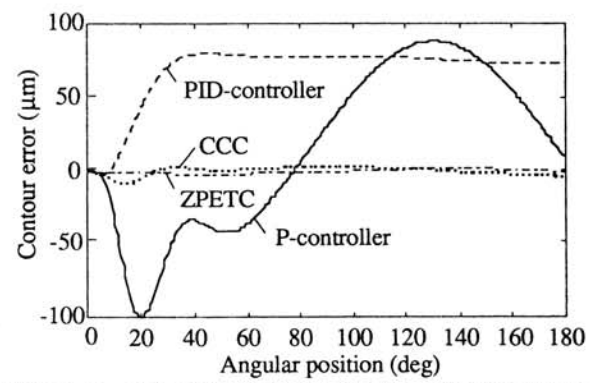


Figure 4: Examining tracking ability and the effect of mismatch in axial parameters for different servo-controllers. Conditions: 5% mismatch in open-loop gains and 40% mismatch in time constants, feedrate = 1.5 m/min (= 59 ipm), radius of circle = 20 mm, no disturbances, no modeling error in ZPETC.

Modeling error. Two limitations of the ZPETC method were not considered in the above simulations. First, as stated in Section 4, the design of a feedforward controller requires knowledge of the exact model of the drive dynamics. In practice, the control designer does not have a perfect knowledge of the drive model, and the model used in the feedforward controller will be different to the actual drive dynamics. Consequently the practical system will result in a position error. Figure 5 demonstrates the sensitivity of the ZPETC method to the modeling error. It is shown that even a small modeling error can degrade the tracking performance of the ZPETC method. As compared to the CCC method (which does not require knowledge of plant parameters), ZPETC can provide a better tracking performance only when the modeling error is less than 0.5%. This limitation, however, is not realistic. Modeling errors of 2% to 5% or even higher in some parameters are more realistic.

Saturation. The other limitation of the ZPETC method is the saturation of the control commands that the computer generates. For proper operation, the ZPETC method needs a very large control command in the transient state to overcome the axial error caused by the drive inertia. The large control command will saturate in a practical CNC system. Consequently, the ZPETC is strongly limited by the saturation constraint. In contrast, the P, PID, and cross-coupling controllers are not influenced by the saturation condition.

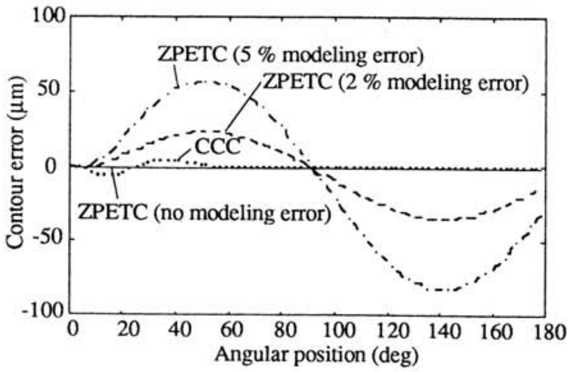


Figure 5: The effect of modeling error on ZPETC method. Conditions: Feedrate = 0.75 m/min (= 30 ipm), radius of circle = 20 mm, no disturbances, no mismatch in axial parameters.

Disturbances. Figure 6 shows the disturbance rejection ability for each of the four control algorithms. The simulation results show that (1) the CCC and PID controller have a good ability in disturbance rejection (CCC is the best), and (2) P-controller and ZPETC have very poor performances in disturbance rejection.

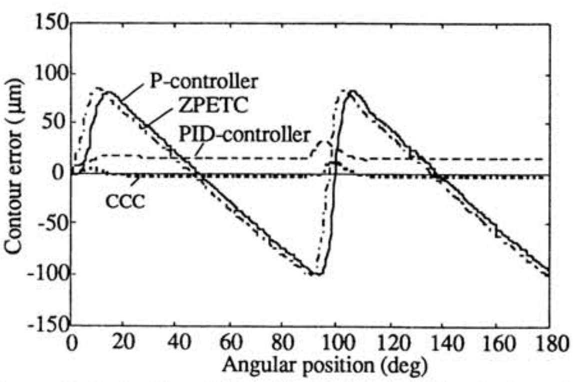


Figure 6: Rejection ability of disturbances (simulation of a circular motion for different servo-controllers). Conditions: Feedrate = 0.75 m/min, radius of circle = 20 mm, no mismatch in axial parameters, no modeling error in ZPETC.

6.2 Experimental Comparison

The experimental tests were conducted on a 3HP two-axis milling machine. The machine was interfaced with our computer, which allows us to write our own control software and test it on this real system. For this paper, linear and circular motions were tested, and the experimental results are shown in Figures 7 and 8.

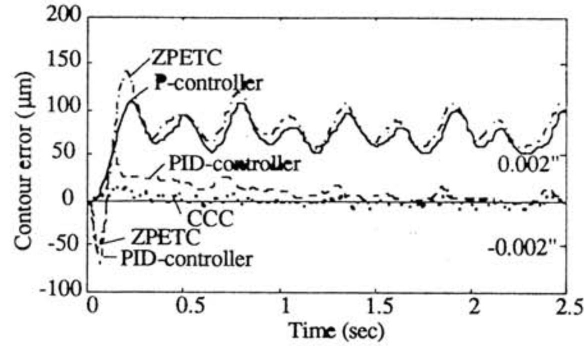


Figure 7: Experimental results of a straight-line motion for different servo-controllers. Conditions: Feedrate = 1.2 m/min (= 47 ipm), angle between straight line and the X-axis = 26.6^0.

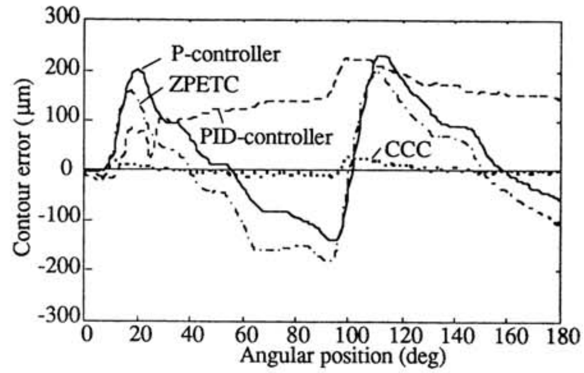


Figure 8: Experimental results of a circular motion for different servo-controllers. Conditions: Feedrate = 1.5 m/min (= 59 ipm), radius of circle = 20 mm.

As can be seen in Figure 7, the ZPETC method results in the worst performance in linear cuts. The ZPETC, as well as the P controller, cannot provide a good disturbance rejection ability (see Section 6.1). Moreover, the ZPETC results in an additional error due to the modeling error, whereas it doesn't exist with P controller. The PID controller, as can be seen in Figure 7, results in a significant overshoot at the transient state (without programmed acceleration). In addition, it also causes large overshoots at the end of the cuts. To remedy this drawback, pre-programming of acceleration and deceleration periods is required, whereas they are not needed with CCC, P-controller, and ZPETC methods. Adding acceleration and deceleration periods will increase the cutting time. Overall, the CCC method provides the best performance.

A circular motion has been also tested on the milling system (see Figure 8). According to Equation 2, the increase in the feedrate makes the contour error due to trajectory tracking more significant. At high feedrates, the PID controller failed; it cannot provide a good tracking. The ZPETC method provides better tracking compared to the P and PID controllers. Nevertheless, the CCC is the only method that can provide a small contour error under such circumstances.

7 CONCLUSIONS

Existing servo-controllers for contouring applications have been classified and tested in this paper. According to the simulations and experimental results, a comparison of these servo-controllers is summarized in Table 1.

Table 1: The evaluation of servo-controllers.

	P control	PID control	Feedforward	CCC
Tracking nonlinear trajectories	Fair	Fair (low f) Poor (high f)	Excellent (1) Fair (2)	Good
Axis mismatch	Fair	Good	Excellent (1) Fair (2)	Good
Disturbances	Poor	Good	Poor	Excellent
Special problems		Overshoot at stopping	Performance is sensitive to modeling error and saturation	Requires a fast processor

Comments:

1. Assume no difference between theoretical model and real system.
2. Assume 2% difference between theoretical model and real system.

f = feedrate

Grading: Excellent, Good, Fair, Poor

Based on the comparison, the selection of servo-controllers for different machine tool features and different cutting conditions is suggested in the following:

(1) The P controller works well only when cutting a contour on a machine with small friction, small cutting loads, small mismatch in axial parameters, and conventional feedrates (e.g., 0.25 m/min = 10 ipm).

(2) The PID controller has a good disturbance rejection ability and is more robust to mismatched axial parameters. Its drawbacks are poor tracking ability of nonlinear contours at high feedrates, and in addition, it may result in an overshoot at stopping. Therefore, the PID controller is preferred on low-speed machines.

(3) The feedforward ZPETC method is preferred at high-speed machining when the system model is well known and no varying or nonlinear characteristics exist. High disturbance loads are not allowed with this method unless the feedback loop has already provided an algorithm for good disturbance rejection.

(4) The CCC method provides a good contouring accuracy under any condition, and therefore is the best choice for a servo-control algorithm.

8 ACKNOWLEDGEMENT

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