



PARAMETER OPTIMISATION OF MACHINE TOOL CONTOUR ERROR CONTROLLER

Helder Barbieri Lacerda
Valder Steffen Jr.

Universidade Federal de Uberlândia, Faculdade de Engenharia Mecânica
Av. João Naves de Ávila, 2121 – Bloco 1M – 38400-902 – Uberlândia – MG
helder@mecanica.ufu.br; vsteffen@mecanica.ufu.br

***Abstract.** Contour error motion controllers were firstly designed in the beginning of the 1980's to improve machine tool contouring performance using a different approach. While P, PID, state-feedback and feedforward controllers are intended to reduce the axial positioning errors, the contour error controller has the philosophy that the controller unique objective is the elimination of the contour error. The sources of contour errors in tracking systems can be classified into three categories (Koren & Lo, 1992): mechanical hardware deficiencies (backlash, non-straightness, etc.), process effects (machine deflections, wear, thermal deformation, etc.) and the controller and drive dynamics. The total dimensional error is a combination of the errors from these sources. The first and the second error sources can be minimised by improving the quality of the mechanical hardware or by using compensation techniques. The third set of error sources is frequently overlooked, but it can be the dominant one, especially in the presence of high acceleration rates, common in modern high speed machine tools. Contour error controllers have internal parameters which are difficult to adjust. The objective of this article is to present the optimisation approach employed to get the parameters of 2D and 3D contour error controllers in simulated contouring operations.*

***Keywords:** motion; control; 3D tracking; contour error.*

1. INTRODUCTION

Three dimensional tracking systems are found in robots, milling machines and 3D coordinated tables. The contouring operations can be performed satisfactorily by using stepper motors, with the main advantages of low cost and reliability. There is a necessity to develop more accurate contour control systems, effective to plane and spatial paths, tracked at feedrate up to 40 m/min. This is one of the main subjects of investigation in HSM (High Speed Machining) technology research. With the increase of axes feedrate, high acceleration rates appear, which combined with friction, backlash, machine deflection and thermal deformation, results in difficulty to follow the desired trajectories. There are many important applications in the industry, like die making (2D and 3D), automotive and aerospace components, cutting tools, prototyping, model building, etc.

The contour error controller (CEC) was idealised by Koren (1980) and the unique objective is to reduce the orthogonal deviation from the desired trajectory, which is called contour error. It is a non-linear, multivariable controller and utilises signals from the axes position sensors and from the interpolator of the machine to generate the corrective signals to the motors, in order to match the actual and the desired trajectory. This approach couples the axes. The CEC works simultaneously with the feedback axial controllers (Åstrom & Hägglund, 1995), helping them. It has been applied to improve the tracking performance on biaxial systems, like in the works of Srinivasan & Kulkarni (1990), Chiang & Liu (1991) and Lacerda & Belo (1997). The results from the literature show that

an improvement always can be obtained in the plane. In some cases, a 20:1 reduction in the contour error was reported. A problem, common to all tracking systems, is the fact that a corrective action is taken only after a deviation is detected. A particular problem of CEC is the lack of a suitable technique to adjust its gains. The objective of this work is to present an optimisation technique applied to determine the parameters of a milling machine contour error controller, simulated with the Matlab/Simulink[®] software (Hicklin et al., 1992).

2. MILLING MACHINE SIMULATOR

The milling machine simulator was presented in Lacerda and Belo (2000). In this work, the chosen configuration is that where the Y-axis bears the X-axis and the Z-axis has an independent motion. The inertia relation between the X, Y and Z axis is 10:20:1. Each one consists of motor, coupling, ballscrew and carriage. The combined elasticity of the ballscrew, bearings and coupling is represented by a stiffness coefficient. There is Coulomb friction in the ballscrew and guideways. Inertia, backlash and cutting forces are the other disturbance effects. There are thermal deformations in all these elements, but they were not considered here, because the axis temperature variations were supposed small. Guideways and ballscrew pitch errors were also not considered. The three axes are primarily controlled by three PID controllers and the CEC works simultaneously, helping them.

3. 3D CONTOUR ERROR CONTROLLER

The application of CEC on 3D systems is rarely found. Tarng et al. (1997) describe a contour error model suitable to 3D paths, but the tests are restricted to circular paths in the XY plane. The Erkorkmaz & Altintas (1998) contour error model is used here to make the estimation of the contour errors. The contour error vector is calculated in real time by using data from the machine interpolator and the axial positions. The advantage is that the magnitude and the components of the contour error are computed. The contour error signal feeds an internal PID controller and the resulting corrective signal is distributed to the motors proportionally to the axis inertia and the magnitude of the contour error vector component. Figure 1 shows a simplified block diagram made with Simulink[®] software. The outputs to the motors are added to control signals coming from the axial controllers. The tests results showed that the contour error mathematical model is accurate enough and the tool path deviations were always reduced. The authors observed that there is no available technique to set the parameters of the embedded PID controller and decided to use a numerical optimisation technique to solve this problem.

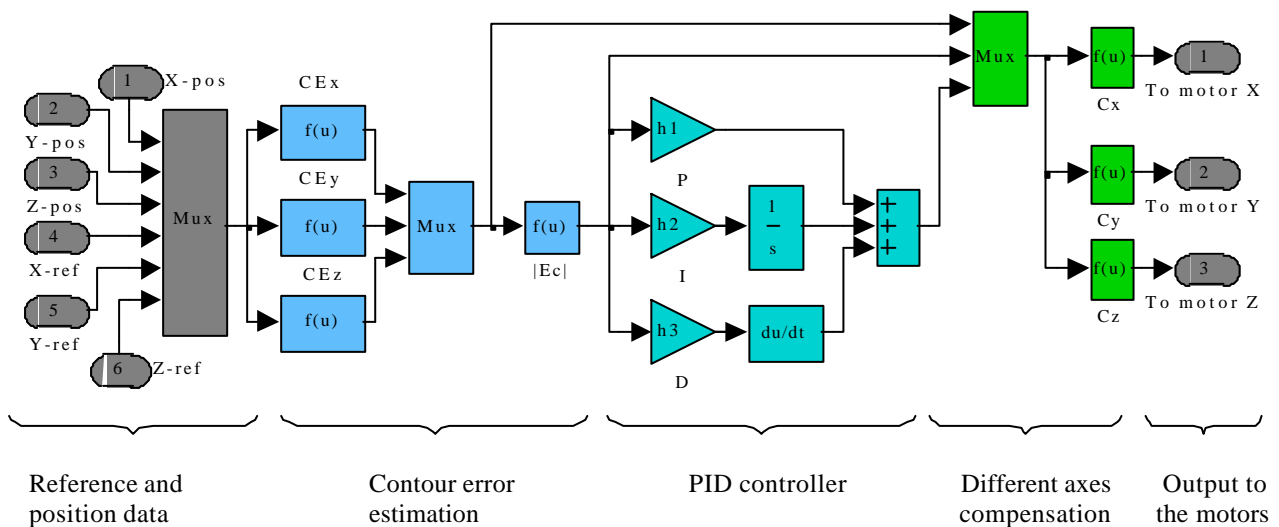


Figure 1. Simplified block diagram of 3D CEC

4. OPTIMISATION SOLUTION

The function *constr* of the Matlab Optimisation Toolbox finds the constrained minimum of a scalar function of several variables, starting at an initial estimate. This is called *constrained nonlinear optimisation* and is mathematically stated as:

$$\text{minimize } f(\mathbf{X}), \text{ subject to: } g(\mathbf{X}) \leq 0$$

The optimisation approach consists of the minimisation of the magnitude of the quadratic contour error. The design variables (\mathbf{X} vector) are the proportional, integral and derivative gains of the embedded PID controller. The unique constraint is that the motor applied voltage is less than 160 volts. A Matlab program was written to link the function *constr* to the block diagram containing the milling machine simulator. The program also normalises the design variables vector in the range 0-100% of the search space. Then, 0% corresponds to the lower bound and 100% to the upper bound. This detail is important to the algorithm performance.

The first step was the optimisation of the gains of the individual axial PID controllers. The objective function is the quadratic axial error, which is the difference between the desired and the actual position of a reference point when tracking a sinusoidal trajectory at 20 m/min. The constraint is the same as cited before. The results can be seen in Tab. (1).

Table 1. Axial controllers optimisation results

		X-axis	Y-axis	Z-axis
Gains	Proportional	$1,21 \times 10^5$	$1,23 \times 10^5$	$4,30 \times 10^3$
	Integral	$4,00 \times 10^7$	$3,70 \times 10^7$	$7,13 \times 10^6$
	Derivative	$5,35 \times 10^2$	$7,15 \times 10^2$	$2,58 \times 10^1$
Number of iterations		61	194	90
Ratio in objective function (f_i/f_f)		97	26	21

5. 2D TEST

The virtual milling machine axial controllers were adjusted with the previously obtained optimal gains shown in Tab. (1). The 2D test objective is the optimisation of the gains of the CEC's internal PID. A contouring operation is performed in the XY plane, which consists in tracking a 200 mm diameter circle with 20 m/min feedrate. The results are in Tab. (2). Figure 2 shows the contour error during the test in the initial situation (CEC is inactive) and after the optimisation procedure. It can be observed a significant reduction in the contour error, due to the optimisation procedure.

Table 2. CEC optimisation results (2D test)

CEC gains	Proportional	$1,84 \times 10^5$
	Integral	$1,01 \times 10^5$
	Derivative	$3,60 \times 10^1$
Number of iterations		121
Ratio in objective function (f_i/f_f)		79

2D TEST RESULTS

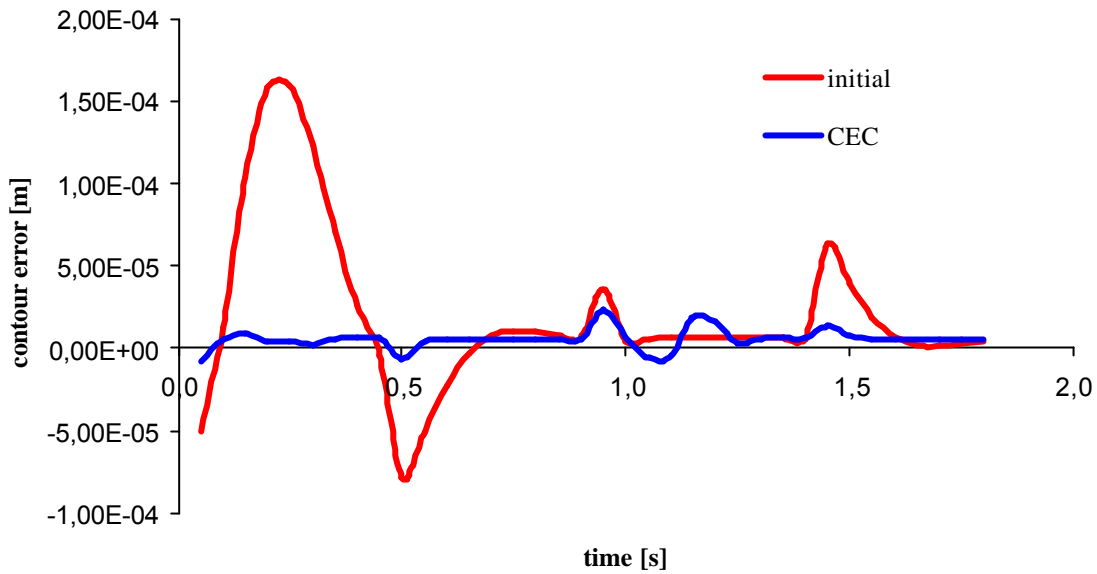


Figure 2. Results of the 2D test. Circle diameter 200 mm. Feedrate 20 m/min.

6. 3D TEST

The 3D test objective is the optimisation of the gains of the CEC's internal PID when tracking a helical trajectory with 200 mm diameter and 200 mm height with 20 m/min feedrate. The results are in Tab. (3). Figure 3 shows the magnitude of the contour error during the test in the initial situation (CEC is inactive) and after optimisation. It can be observed that there was also a significant reduction in the contour error due to the optimisation procedure.

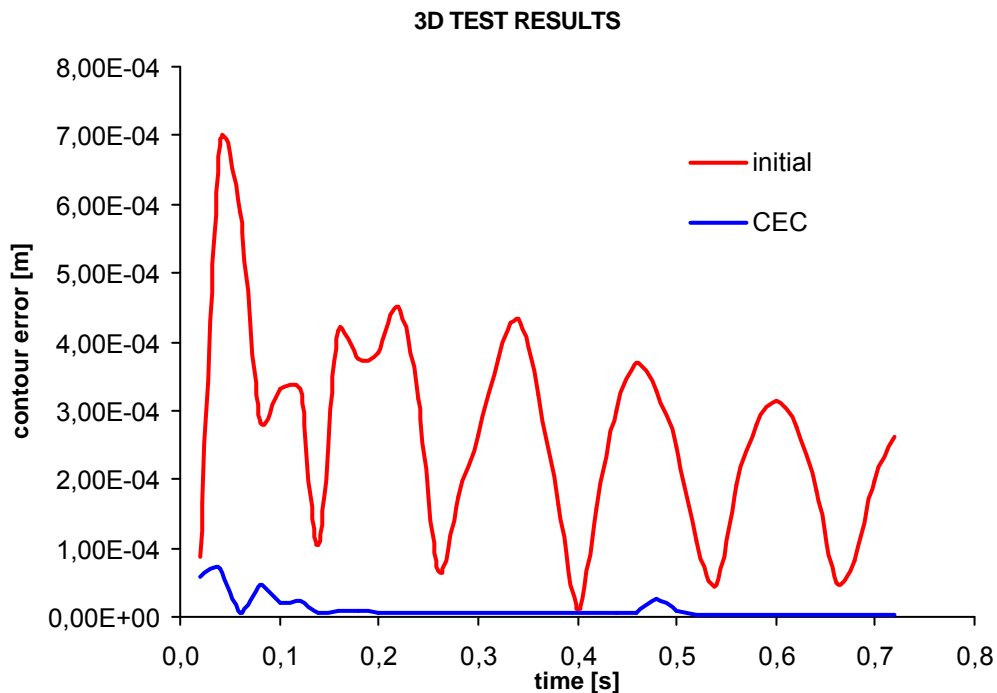


Figure 3. Results of the 3D test. Helical path with 200 mm diameter and height. Feedrate 20 m/min.

Table 3. CEC optimisation results (3D test)

CEC gains	Proportional	$2,40 \times 10^4$
	Integral	$1,44 \times 10^4$
	Derivative	$9,15 \times 10^1$
Number of iterations		178
Ratio in objective function (f_i/f_f)		51

7. CONCLUSIONS

The milling machine simulator can reproduce with relative success the dynamical behaviour of an actual machine tool, as was shown by validation tests in a previous work (Lacerda, 1998). The Erkorkmaz & Altintas (1998) 3D contour error model is relatively simple and accurate, giving a good estimation of the tool path deviation in the three dimension space. The CEC always produce an improvement in the performance and can be applied successfully to any 3D tracking system. The optimisation approach is a powerful tool to obtain the optimum gains of axial and contour error controllers. The tests results in this paper showed that there was an important reduction in the deviations from the given tool path, due to the optimised controller parameters.

REFERENCES

- Ästrom, K. and T. Hägglund, 1995, "PID Controllers: theory, design and tuning", Instrument Society of America, Research Triangle Park, NC, USA.
- Chuang, H. and C. Liu, 1991, "Cross-coupled adaptive feedrate control for multiaxis machine tools", ASME J. Dyn. Sys., Meas Control, v. 113, p. 451-457.
- Erkorkmaz, K. and Altintas, Y., 1998, "High speed contouring control algorithm for CNC machine tools", Proceedings of the ASME Dynamic Systems and Control Division, 1998 ASME International Mechanical Engineering Congress and Exposition, DSC 64 (1998), p. 463-469.
- Hicklin, J. et al., 1992, "Simulink - A program for simulating dynamic systems", The MathWorks Inc., Massachusetts, USA.
- Koren, Y., 1980, "Cross-coupled biaxial computer control for manufacturing systems", ASME J. Dyn. Sys., Meas. Control, v. 102, p.265-272.
- Koren, Y. and C. Lo, 1991, "Variable-gain cross-coupling controller for contouring", Annals of the CIRP, v. 40, n. 1, p. 371-374.
- Koren, Y. and C. Lo, 1992, "Advanced controllers for feed drives", Annals of the CIRP, v. 41, n. 2, p.689-698.
- Lacerda, H. B. and E. M. Belo, 1997a, "Application of a PID+Fuzzy controller on the motion control system in machine tools", J. of the Brazilian Soc. of Mechanical Sciences, Vol. XXI, n°3, p.414-422.
- Lacerda, H. B., 1998, "A contour error controller for high speed CNC machines" (In Portuguese), PhD. Thesis, University of São Paulo, São Carlos, SP, Brazil, 127 p.
- Lacerda, H. B. and E. M. Belo, 2000, "A modified contour error controller for a high speed XY table", J. of the Brazilian Soc. Of Mechanical Sciences, Vol. XXII, N° 3, p. 443-455.
- Lacerda, H. B., 2001, "A contour error controller for 3D tracking systems", Proceedings of the IX DINAME - International Conference on Dynamic Problems in Mechanics, p. 3-8, Florianópolis (SC), 5-9 March.
- Srinivasan, K. and P. K. Kulkarni, 1990, "Cross-coupled control of biaxial feed drive servomechanisms", ASME J. of Dyn Sys, Meas. and Contr., Vol. 112, p.225-232.
- Tarng, Y., Chuang, H. and Hsu, W., 1997, "An optmisation approach to the contour error control of CNC machine tools using genetic algorithms", Int J. Adv. Manuf. Tech., Vol. 13, p. 359-366.