FUZZY LOGIC CROSS-COUPLING CONTROL

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ABSTRACT

In order to achieve high precision contour machining, it is not enough to utilize individual axis controllers such as PID or feedforward controllers. These axial controllers do not guarantee the reduction of contour errors, which are as important as the axial position errors in contour machining. Multi-axis sophisticated controllers are needed to reduce contour errors.

One of the methodologies to address this problem is cross-coupling control. The control objective of the cross-coupling method is the reduction of the contour errors rather than the axial position errors, thereby considerably improving the contouring accuracy. However, the existing cross-coupling controllers cannot overcome machine tool hardware deficiencies such as backlash and friction, and they are not adequate for high-feedrate machining which causes long *transient distances*.

To solve these problems, we developed a new cross-coupling controller with a rule-based fuzzy logic control. It is known that fuzzy logic controllers provide a faster response (which is essential during the transient periods) than conventional controllers such as the PID controller. In this fuzzy logic cross-coupling control (FLCCC), a friction compensation strategy is included to reduce the contour errors in the low-velocity range. We implemented the FLCCC method on a milling machine and the experimental results show improved contour accuracy.

1. INTRODUCTION

In order to produce parts of better quality in industry, many efforts have been made to develop more accurate computerized numerical control (CNC) systems. In particular, advanced servo-control algorithms for the feed drives such as feedback control, feedforward control and adaptive control have been implemented [4].

In conventional CNC machines, each individual axis has an axial position error which is the difference between a desired position and an actual position: the former is the output from an interpolator in a CNC system, and the latter is available through a position feedback device such as an encoder. Since the control loop is separate for each axis, contour errors (i.e., deviations from a desired path) can be caused due to a mismatch in the loop parameters and a difference in the external disturbance on each axis. In addition, a nonlinear contour shape can cause large contour errors, especially at high feedrates.

Since the axial controllers do not guarantee small contour errors, it is necessary to use more sophisticated controllers, whose control objective is the reduction of contour errors rather than axial position errors. One of the methodologies to address this problem is cross-coupling control [2, 3, 4, 5]. However, the existing cross-coupling controllers cannot overcome machine tool hardware deficiencies, such as backlash and friction, and they are not adequate for high-feedrate machining which causes long transient distances.

In this study, we have developed a new cross-coupling controller with a rule-based fuzzy logic control. It is known that fuzzy logic controllers provide a faster response (which is essential for the shorter transient periods) than conventional controllers such as the PID controller. In this fuzzy logic cross-coupling control (FLCCC), a friction compensation strategy is included to reduce the contour errors in the low-velocity range. Consequently, this FLCCC can be applied to a wide range of feedrates in contour machining. We have implemented the FLCCC on a CNC milling machine and the experimental results show that this controller is able to achieve high contour accuracies.

2. FUZZY LOGIC CROSS-COUPLING CONTROLLER (FLCCC)

As mentioned previously, small axial position errors do not always guarantee small contour errors, which are more important from the point of view of the contour accuracy. Figure 1 shows an experimental result which represents the relationship between the axial position errors and the contour errors in the case of one-cycle biaxial circular motion with a conventional PID control for each axis. Here, the basic length unit (BLU) which corresponds to a system resolution is 10 μm. From this example, it is obvious that the contouring accuracy does not necessarily depend on axial position tracking accuracy. If it were linearly dependent, then the graphs would be straight lines.

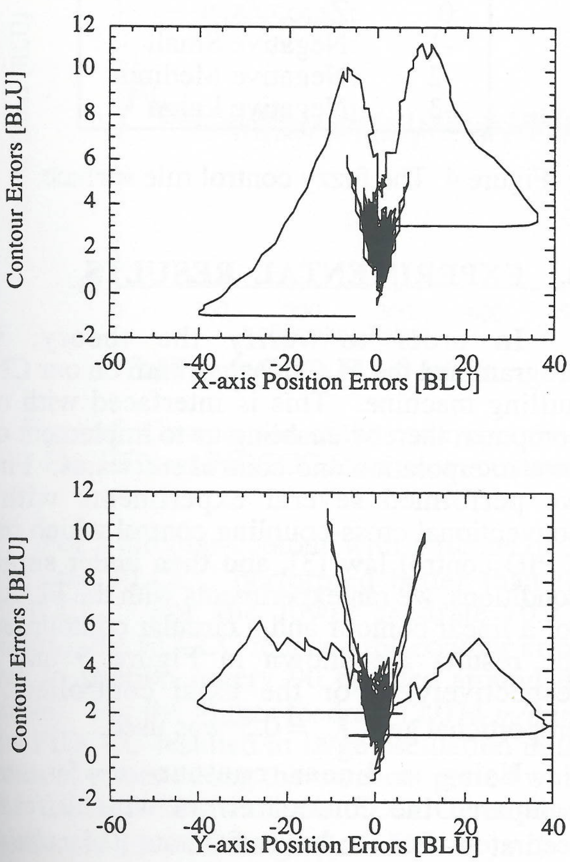


Figure 1 The relationship between axial position errors and contour errors.

A block diagram of the proposed cross-coupling control for two axes is shown in Figure 2. The contour ε is calculated based on the contour error mathematical model by Koren and Lo [3]:

$$\varepsilon = -E_x C_x + E_y C_y \qquad (1)$$

where C_x and C_y are the functions of contour geometry and axial position errors E_x and E_y, respectively. For each axis, we have used a proportional axial controller with the same gain K_p. In Figure 2, K_x and K_y represent the system open-loop gains multiplied by the encoder gains for the x and y axes, respectively, and τ_x and τ_y are the time constants of the axial drives. Each axial position error is calculated in real time as the difference between a reference position command and a position feedback from an encoder, and subsequently fed into the above contour error model. Then, through the fuzzy logic control law and the multiplication by the gains C_x and C_y, the control commands U_x and U_y are generated and sent to the power amplifiers to drive the motors. We use the proportional and differential (PD) type of fuzzy logic control (FLC) (its structure is shown in Figure 3) because of its fast transient responses. Thus, it is necessary to add an integral controller to eliminate steady-state contour errors. Accordingly, an integral controller was used in parallel with the FLC and included in the FLC block in Figure 2.

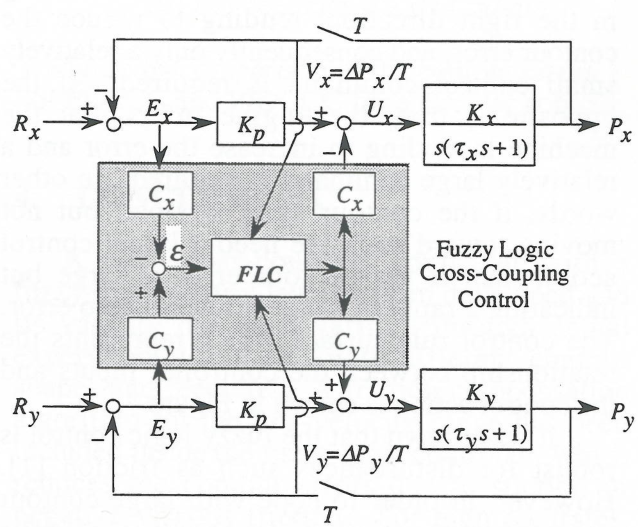


Figure 2 The overall structure of FLCCC.

2.1 Fuzzy Logic Control

The structure of the FLC, which is the core of the FLCCC, is shown in Figure 3. The inputs to the FLC are (i) the contour error at the current time step (ε), and (ii) the change in the contour error between the previous and current sampling time steps ($d\varepsilon$). Thus, the rate of change in the contour error and its direction as well as the magnitude of the contour error are associated with determining the control actions. We have defined seven fuzzy sets for the controller inputs (E_c and dE_c) and the controller output (U_c), and labeled them as positive large, positive small, negative medium, etc.

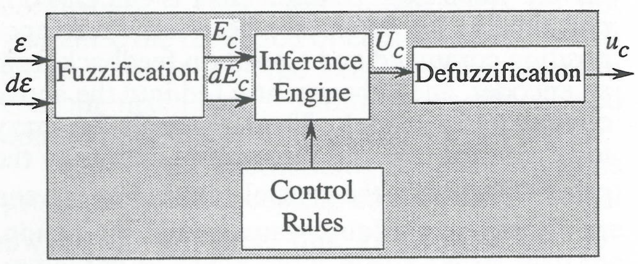
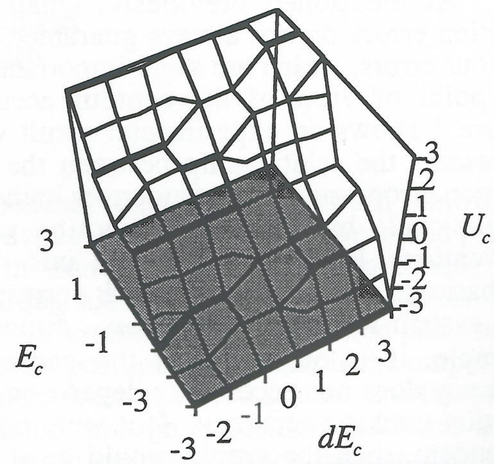


Figure 3 The structure of fuzzy logic controller in the FLCCC.

The fuzzy control rule base in the cross-coupling control was established based on the following principle. If the contour at the current time step is closer to the zero contour error than the error at the previous time step, the engine inside the FLC infers that the machine is heading in the right direction, tending to reduce the contour error, and consequently only a relatively small control command is required. If the opposite is true, the engine infers that the machine is tending to increase the error and a relatively large command is required. In other words, if the contour error is small but not moving toward zero, we need a larger control action than if the contour error is large but indicating a rapid movement toward zero error. The control rule surface which represents the relationship between the controller inputs and the control action is shown in Figure 4.

It was shown that the fuzzy logic control is robust for disturbances such as friction [1]. However, in order to cope with large contour errors due to stiction or negative viscous friction, it is necessary to build a friction compensation algorithm inside the FLC. Based on the velocity feedback, we performed the compensation by enlarging the centroid of the controller output membership functions in the low-velocity range, namely under 12 *mm/sec*.



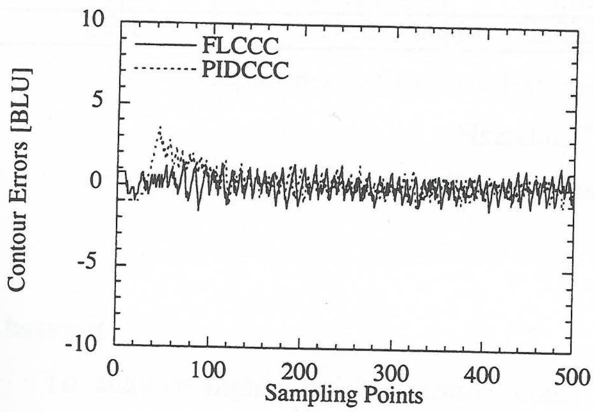
3	:Positive Large
2	:Positive Medium
1	:Positive Small
0	:Zero
-1	:Negative Small
-2	:Negative Medium
-3	:Negative Large

Figure 4 The fuzzy control rule surface.

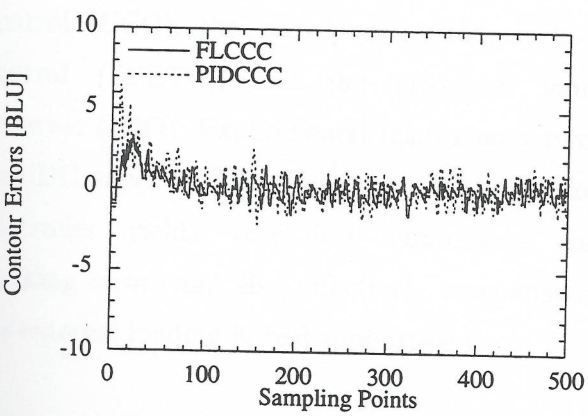
3. EXPERIMENTAL RESULTS

In order to verify the theory, we programmed the FLCCC algorithm on our CNC milling machine. This is interfaced with our computer, thereby enabling us to implement our own interpolation and control softwares. First, we performed several experiments with a conventional cross-coupling control which uses a PID control law [3], and then under similar conditions, we ran experiments with the FLCCC for a linear contour and a circular contour, and the results are shown in Figure 5 and 6, respectively. For the axial controllers, a proportional gain $K_p = 0.5$ was used.

Using a linear contour $x = 5y$, we compared the contour errors with different feedrates. For the lower feedrate (0.1 *m/min*), the FLCCC with the friction compensation arrested the contour errors due to static friction, while the PID cross-coupling control (PIDCCC) resulted in large initial contour errors because of stiction. For the higher feedrate (1.5 *m/min*), the FLCCC showed better results than the PIDCCC not only during the transient period but also along the entire path.



(a) For feedrate = 0.1 *m/min*

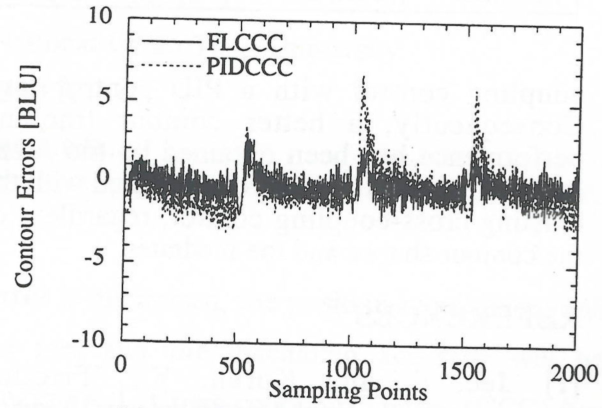


(b) For feedrate = 1.5 *m/min*

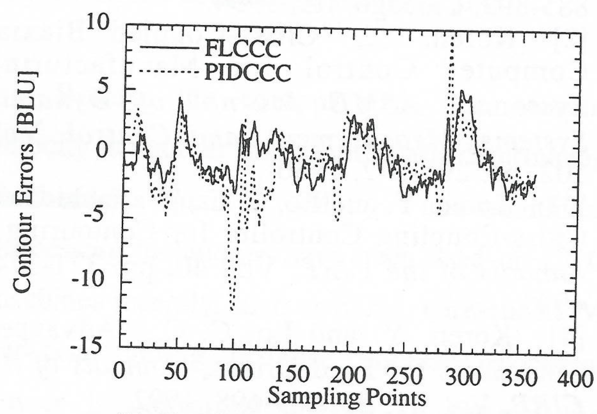
Figure 5 Comparison of the contour errors of FLCCC and PIDCCC for a linear contour.

For a circular contour with a radius of 20 *mm*, the FLCCC performed better than the PIDCCC. For the lower feedrate (0.377 *m/min*), the FLCCC reduced the contour errors due to stiction (every 90 degrees around the circle). For the higher feedrate (2.074 *m/min*), the PIDCCC resulted in large oscillation in the contour errors during the transient period while the contour errors of the FLCCC remained within the ±5 BLU range (1 BLU = 10 μm). If we further increased the feedrate, the PIDCCC caused a saturation in control command, and the contour errors diverged. The FLCCC, however, continued to operate.

The experimental results are summarized in Table 1. We compared the absolute maximum contour errors during the transient periods and the root mean square (RMS) values of contour errors at the steady-states.



(a) For feedrate = 0.377 *m/min*



(b) For feedrate = 2.074 *m/min*

Figure 6 Comparison of the contour errors of FLCCC and PIDCCC for a circular contour.

4. CONCLUSIONS

A new cross-coupling controller with a fuzzy logic control law has been developed and its validity has been verified through actual experimental analyses with different contour shapes and feedrates. A friction compensation algorithm for the low-velocity range has been included inside the fuzzy logic controller, which reduces the contour errors due to stiction or negative viscous friction. For high feedrates, this new approach has provided much better transient responses than the conventional cross-

Table 1 Comparison of the contour errors (unit: 10 μm)

		Linear Contour		Circular Contour	
		Transient	Steady-state	Transient	Steady-state
Low Feedrate	PIDCCC	3.53	0.52	6.73	1.36
	FLCCC	1.56	0.56	3.10	0.68
High Feedrate	PIDCCC	6.47	0.83	11.99	2.72
	FLCCC	3.33	0.53	5.41	1.95

coupling control with a PID control law. Consequently, a better contour tracking performance has been obtained by the fuzzy logic cross-coupling control compared with the existing cross-coupling control, regardless of the contour shapes and the feedrates.

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