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Improving CNC contouring accuracy by robust digital integral sliding mode control

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ABSTRACT

Integral sliding mode control (ISMC) has been employed and shown to improve contouring accuracy in the presence of external disturbances and model uncertainties. An ISMC controller directly reduces the tracking errors of each individual axis, thereby reducing the overall contour errors indirectly. An ISMC controller drives the system dynamics back onto the sliding surface if there exists a deviation from the predefined surface. In the design of an ISMC controller, it is crucial to choose an appropriate sliding surface as this has a great impact on system performance and on chattering. In current approaches, the sliding surface is chosen largely based on a rule of thumb which is only applicable for systems with open-loop poles having imaginary parts. In this paper, an approach is presented to design the sliding surface using principles of robust digital control so that both the regulation and robustness requirements can be satisfied. The natural frequency of the dominant closed-loop poles is chosen such that the modulus of the output sensitivity function lies within the robustness bounds. Resonant pole-zero filters are then used to reshape the output sensitivity function in specific frequency regions. Experiments showed that when the modulus of the output sensitivity function is kept within the robustness bounds, chattering can be avoided and the contour errors resulting from vibrations can be reduced. The introduction of a resonant pole-zero filter also allowed the attenuation band to be expanded so that the low frequency components of the contour errors are attenuated.

1. Introduction

There is an increasing demand on improving contouring accuracy in CNC machines [1,2]. The term contour error is defined as the error component orthogonal to the desired trajectory (i.e., the deviation of the cutter location from the desired path) [3]. Approaches used for reducing or eliminating contour errors can generally be classified as either axial tracking control or contouring control. In the former, the control objective is the design of better controllers to reduce the tracking, or following, errors of the individual axes. With reduced axial tracking errors, the contouring errors are correspondingly reduced. In the contouring control approach, the control objective is focused on reducing the contour errors directly. It has been shown that small or no contour error can be achieved even when there are significant axial tracking errors which can be made to cancel each other's effect [4,5].

Contouring control approaches include the cross-coupled controller (CCC) first proposed by Koren [6] and its various derivatives [7–10]. While CCC can work well when properly designed, its disadvantage is that the design of the controller needs to change depending upon the contour being generated. Otherwise contouring performance degrades. Although contouring control has generally be applied in a Cartesian coordinate system, it has also been applied in a task polar coordinate system [11–13]. In a single machining operation on a CNC machine, invariably various types of contours are required. As such, unless the CCC-based controller is made intelligent enough to change its design online according to the contours being generated, contouring performance, and the accuracy of the machined parts, will be degraded.

If the tracking errors of individual axes can be significantly reduced or eliminated through the improved design of their axial-tracking controllers, then good contouring performance will be achieved regardless of the type of contours required. The general idea for many tracking control approaches is to place a pre-compensator before the servo control loop. For minimum-phase plants, the pre-compensator is the inverse of the axial dynamics. For nonminimum-phase plants, the pre-compensator is an approximation of the inverse of the axial dynamics at low frequencies. Zero phase error tracking control (ZPETC) [14] is a typical example of this approximation. Although inverse control or ZPETC is theoretically feasible, in practical situations contouring accuracy has been shown to be not satisfactory [6]. This is because contouring performance is affected by errors in the dynamic

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model used in the design of the controller as well as by measurement noise and disturbances encountered in real situations.

To overcome disturbances and model uncertainties, one promising control approach is sliding mode control (SMC) [15]. The use of PD control with SMC has been reported to significantly reduce tracking errors in a robotic system [16]. An SMC controller with a nonlinear sliding surface has also been reported to improve the contouring accuracy in machining [17].

One design of SMC consists of an equivalent control and a switching control. The equivalent control is derived from the definition of the sliding surface [18] and the switching control forces the system to slide along the surface. As switching control usually takes a discontinuous form [19], undesirable chattering in the control signals often results. To address this problem, integral sliding mode control (ISMC) which employs integral control action [20–22], has been developed. By including estimates of the disturbances and integral control action into the controller, the system dynamics are controlled to slide along a pre-designed sliding surface, thereby achieving a predefined dynamic performance. By using the same model of the sliding surface for both the *X*- and *Y*-axes, matched axial dynamics can be achieved leading to improved contouring accuracy [22,23]. ISMC has also been reported in fast servo diamond turning [24,25].

In a previous study using the ISMC controller for contouring control, very good results were achieved with almost zero average contour errors [22]. However, chattering about the mean error was a problem. It was found that the choice of the sliding surface significantly affects chattering. A rule of thumb approach, arrived at by trial-and-error, was used for choosing the sliding surface to reduce chattering.

In this paper, an approach to choosing the sliding surface for ISMC, based on the framework of robust digital control, will be presented. The sliding surface of an ISMC controller is determined by the closed-loop poles. Because the identified model inevitably has model inaccuracies and the real plant is subject to external disturbances and measurement noise, the choice of a sliding surface needs to incorporate the consideration for a robustness margin. Therefore, the set of closed-loop poles should be chosen in such a way that the robustness constraints in terms of the output sensitivity function can be respected. Experimental results show that the magnitude of contour errors resulting from chattering can be significantly reduced by an appropriately chosen sliding surface. While the overall system response is shaped mainly by the dominant poles, resonant pole-zero filters can be used to shape the frequency response at specific frequencies. In the work presented here, a resonant pole-zero filter was used to expand the attenuation band so as to attenuate low frequency disturbances.

2. Experimental setup

Contouring experiments were carried out on an *X*–*Y* table as shown in Fig. 1(a). The *Y*-axis was placed on top of the *X*-axis, thus resulting in different axial dynamics of the two axes. Each axis is driven by a Yaskawa SGMJV-04ADE6S AC servo motor with its motor drive set in velocity control mode as shown in Fig. 1(b). Position feedback was implemented through an encoder with a resolution of 8096 pulses/rev. The ball screw has a 4 mm pitch giving a linear travel resolution for the position feedback of 0.977 μm/pulse. An Intel Core I5 3.1 GHz PC operating under Ubuntu 12.04 Linux with the RTAI real-time kernel patch was used as the control computer with an Adlink PCI-8136 interface card. LinuxCNC was used as the CNC control platform on which both the ISMC controller and the PCI-8136 driver were implemented as real-time modules. The sampling/control frequency used was 1 kHz.

For controller design, closed-loop identification [26] is adopted so as to counteract the drifting of a servo motor when the power is on. A pseudo-random binary sequence (PRBS) is used as the excitation signal. The identified open-loop models, as enclosed in the dashed line in Fig. 1(b), for the *X*- and *Y*-axes of the *X*-*Y* table are listed in Table 1. The poles for the *X*-axis model are (1.0, 0.9476, −0.7618) and those for the *Y*-axis model are (1.0, 0.9319, 0.2072). It can be noted that, except for the pole at 1 due to the integration from velocity to position, the other two poles of both the axes lie on the real axis. Therefore the rule of thumb for choosing the sliding surface in [22], which is only applicable to models with conjugate poles, cannot be used in this work.

3. Contour error

3.1. Computation of contour error

The contour error for a linear contour was computed using

$$\varepsilon = -e_x \sin\theta + e_y \cos\theta \quad (1)$$

where e_x and e_y are the tracking errors of the *X*- and *Y*-axes, respectively, and θ is the angle the linear contour makes with the *X*-axes. For a circular contour, the contour error is computed using

$$\varepsilon = \sqrt{(x-x_0)^2+(y-y_0)^2} - R \quad (2)$$

where (x, y) are the coordinates of the actual position of the machine tool, (x_0, y_0) the coordinates of the center of the desired circular contour and R its radius.

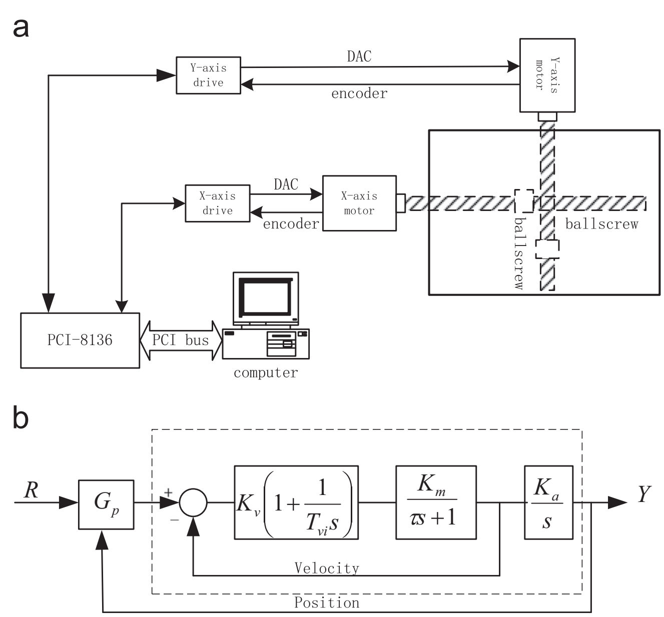

Fig. 1. Experimental *X*–*Y* table: (a) Schematic diagram for *X*–*Y* table; (b) block diagram for axial servo drive system.

Table 1
Models of the *X*- and *Y*-axes, for $d=3$.

$\frac{y(t)}{u(t)} = \frac{q^{-d}B(q^{-1})}{A(q^{-1})}$	q^0	q^{-1}	q^{-2}	q^{-3}
$B_x(q^{-1})$	5.172e−3	1.173e−3	−2.394e−3	0.0
$A_x(q^{-1})$	1.0	−1.185	−0.5361	0.7219
$B_y(q^{-1})$	1.150e−3	−1.422e−3	6.505e−4	0.0
$A_y(q^{-1})$	1.0	−2.139	1.332	−0.1931