ISA Transactions xxx (2018) 1–9

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Robust iterative learning contouring controller with disturbance observer for machine tool feed drives

Kenneth Renny Simba [a,b,*], Ba Dinh Bui [d], Mathew Renny Msukwa [a,c], Naoki Uchiyama [a]

[a] *Department of Mechanical Engineering, Toyohashi University of Technology, Toyohashi, Aichi, 441-8580, Japan*
[b] *Directorate of Nuclear Technology, Tanzania Atomic Energy Commission, Arusha, Tanzania*
[c] *Department of Electrical Engineering, University of Dar es Salaam, Dar es Salaam, Tanzania*
[d] *Academy for Safety Intelligence, Graduate School of Engineering, Nagoya University, Nagoya, Aichi, 464-0814, Japan*

ARTICLE INFO

Article history:
Received 18 July 2017
Revised 15 January 2018
Accepted 7 February 2018
Available online XXX

Keywords:
Computer numerical control machines
Controller design
Iterative learning control
Machine learning
Machine tools
Nonlinear control systems
Nonlinear friction compensator

ABSTRACT

In feed drive systems, particularly machine tools, a contour error is more significant than the individual axial tracking errors from the view point of enhancing precision in manufacturing and production systems. The contour error must be within the permissible tolerance of given products. In machining complex or sharp-corner products, large contour errors occur mainly owing to discontinuous trajectories and the existence of nonlinear uncertainties. Therefore, it is indispensable to design robust controllers that can enhance the tracking ability of feed drive systems. In this study, an iterative learning contouring controller consisting of a classical Proportional-Derivative (PD) controller and disturbance observer is proposed. The proposed controller was evaluated experimentally by using a typical sharp-corner trajectory, and its performance was compared with that of conventional controllers. The results revealed that the maximum contour error can be reduced by about 37% on average.

1. Introduction

The rapid growth of technology and demand for precision products have created a need for high speed and precise production and manufacturing systems. Computer numerical control machine tools are being used globally for the production of various parts ranging from pinhole sized such as parts for watches, cameras and computers, to larger ones such as those in automotive and infrastructure parts. To ensure quality for all these variously sized products, precision is crucial.

Nonlinear uncertainties in real control systems result from either disturbance signals or system modelling errors [1–4]. These uncertainties are common and cannot be avoided in practical applications. When a system is approximated by a mathematical model, non-fundamental factors are ignored such as high-frequency dynamics and uncertainties. These uncertainties are crucial in undermining the performance of a dynamical system. In machine tools, which deal with discontinuous trajectories programmed in G-code fashion, the existence of steep curvatures cause rapid changes in acceleration profiles. These types of trajectories contain a wide range of frequencies that can excite resonance frequencies of mechatronic systems leading to mechanical vibrations. In this light, the motion control of machine tools and manipulators has received attention by considering feedback of contouring errors and time-scaling of references [5–9]. The fundamental idea is to minimise contour and tracking errors through path following techniques and to design motion controllers that achieve high-tracking bandwidth with disturbance rejection.

Usually products are manufactured in batches; therefore, the nature of a machine tool operation is repetitive. This repetitive nature allows the design of controllers that learn from previous inputs and modify subsequent inputs to improve system performance in real-time. This type of control is called an Iterative Learning Control (ILC), and has been proven to provide superior system performance [10–16]. The common approach is to design independent controllers for each drive axis by feeding back the tracking errors, and updating the control inputs accordingly. Given that motion trajectory profiles are normally complex, multiple axes must be moved synchronously to obtain the desired profile. Under independent axial controllers, load disturbance or performance variance

* Corresponding author. Department of Mechanical Engineering, Toyohashi University of Technology, Toyohashi, Aichi, 441-8580, Japan.
E-mail addresses: reksi062@gmail.com, rennyk@taec.or.tz (K.R. Simba), buidinhba5@gmail.com (B.D. Bui), rennymatt@gmail.com (M.R. Msukwa), uchiyama@tut.jp (N. Uchiyama).

https://doi.org/10.1016/j.isatra.2018.02.011
0019-0578/

Acronyms

FB	Feedback controller
ILC	Iterative Learning Control
FBF	FB with Friction compensator
FBFD	FB with Friction compensator and Disturbance observer
FBILC	FB with ILC
VILCFD	Variable-gain Iterative Learning Contouring controller with Friction compensator and Disturbance observer

of either drive axis leads to contour errors [17]. In light of this, major current approaches for improving the control performance of feed drive systems are based on contouring control [12,18–22], while a few of them are based on the tracking error of each drive axis [23,24].

Despite the achievements of a few previous studies, it is indispensable to further enhance systems performance by considering contour errors. An iterative learning controller which considers both tracking and contour errors was designed in Ref. [25], and its feasibility was verified by simulation. On the other hand, friction is among the main factors that degrade machine-tool motion accuracy [26]. Friction compensation control in machine tools have drawn the attention of many researchers seeking to improve the motion performance of machine tools. Model-based methods are highly applied because they exactly cancel out the effect of the friction force on feed drives by offering additional driving force equivalent to the estimated friction [26–28]. Meanwhile, in Ref. [29], a friction model that considers a number of friction sources with complex nonlinear properties was proposed. The proposed model considers nonlinearities in high-speed motion, and in addition to linear guides friction, it considers the friction behaviour in the lead screw drives. The friction model was proven experimentally to be superior to existing models such as the one in Ref. [30].

In the present study, a Variable-gain Iterative Learning Contouring controller with Friction compensator and Disturbance observer (VILCFD) is proposed. As compared to conventional ILCs such as the one in Ref. [25], the proposed controller achieved better performance, as can be seen in the reduction of maximum contour errors by about 37% on average.

The rest of this paper is organised as follows: Section 2 defines contour error and explains the dynamics of biaxial feed drive systems. Section 3 describes the design of the proposed contouring controller, which includes a nonlinear friction model. Simulation and experimental results are demonstrated in section 4, followed by concluding remarks in section 5.

2. Preliminaries

2.1. Definition of contour error

Here, the contour error is derived simply from the tracking error in each drive axis, as shown in Fig. 1. It is the perpendicular distance from the actual position to the reference contour. In contrast, the tracking error refers to the difference between the desired and actual positions of each drive axis. The desired position of a point on the machined part at sampling instant t in coordinate frame Σ_w is denoted by $x_d = [x_{d1} \quad x_{d2}]^{\mathrm{T}}$, while $x = [x_1 \quad x_2]^{\mathrm{T}}$ represents the actual position of the feed drive system in Σ_w. The tracking error in each drive axis is defined as

$$e_w = \left[e_{w1}, \quad e_{w2}\right]^{\mathrm{T}} = x_d - x. \tag{1}$$

The coordinate frame Σ_l is attached at x_d and its axis directional vectors are $\mathcal{T}$ and $\mathcal{N}$, which are tangential and orthogonal to the reference position x_d, respectively. Thus, the tracking error vector e_w can be expressed with respect to Σ_l as

$$e_l = \left[e_t, \quad e_n\right]^{\mathrm{T}} = R^{\mathrm{T}} e_w, \quad R = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}, \tag{2}$$

where θ is the inclination of Σ_l to Σ_w.

2.2. Dynamics of feed drive systems

The following decoupled second order system represents the dynamics of a typical feed drive system:

$$M_f \ddot{x} + f_r + d = f, \tag{3}$$

with

$$M_f = \mathrm{diag}\left(m_{f1}, m_{f2}\right), \quad f_r = [f_{r1} \quad f_{r2}]^{\mathrm{T}},$$

$$d = [d_1 \quad d_2]^{\mathrm{T}}, \quad f = [f_1 \quad f_2]^{\mathrm{T}},$$

where m_{fi}, f_{ri}, d_i, and f_i are the mass of the table, friction force, bounded disturbance and driving force on the drive axis i, respectively. Each drive axis is driven by a typical servo motor, whose dynamics is represented as follows:

$$H\ddot{\vartheta} + C_m\dot{\vartheta} + \tau = K_t i_a, \tag{4}$$

with

$$H = \mathrm{diag}\left(h_1, h_2\right), C_m = \mathrm{diag}\left(c_{m1}, c_{m2}\right), K_t = \mathrm{diag}\left(k_{t1}, k_{t2}\right),$$

$$\vartheta = [\vartheta_1 \quad \vartheta_2]^{\mathrm{T}}, \quad \tau = [\tau_1 \quad \tau_2]^{\mathrm{T}}, \quad i_a = [i_{a1} \quad i_{a2}]^{\mathrm{T}},$$

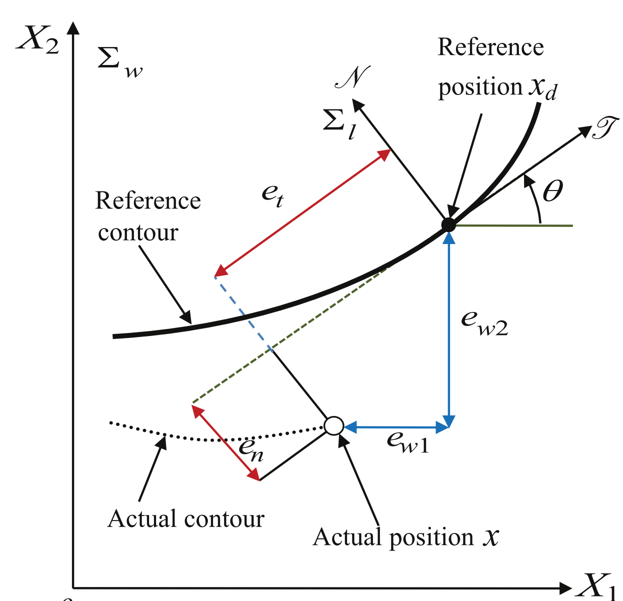

Fig. 1. Definition of tracking and contour errors [29].