Error compensation in machine tools: a neural network approach

JOHN C. ZIEGERT and PRASHANT KALLE
Department of Mechanical Engineering, University of Florida, Gainesville, FL 32611, USA
Received June 1992 and accepted February 1993

For a non-idealized machine tool, each point in the workspace is associated with a tool point positioning error vector. If this error map can be determined, then it is possible to substantially improve the positioning performance of the machine by introducing suitable compensation into the control loop. This paper explores the possibility of using an artificial neural network (ANN) to compute this mapping. The training set for the ANN is obtained by mounting a physical artifact whose dimensions are precisely known in the machine’s workspace. The machine, equipped with a touch trigger probe, ‘measures’ the positions of features on the artifact. The difference between the machine reading and the known dimension is the machine error at that point in the workspace. Using standard modeling techniques, the kinematic error model for a CNC turning center was developed. This model was parameterized by measurement of the parametric error functions using a laser interferometer, electronic levels and a precision square. The kinematic model was then used to simulate the artifact-measuring process and develop the ANN training set. The effect of changing artifact geometry was explored and a machining operation was simulated using the ANN output to provide compensation. The results show that the ANN is capable of learning the error map of a real machine, and that ANN-based compensation can significantly reduce part-dimensional errors.

Keywords: Machine tools, error compensation, neural network

1. Introduction

The machining accuracy of a machine tool is determined in part by the magnitude of deviations in the relative positions of the kinematic elements of the machine tool, which give rise to tool-positioning errors. The most important sources of error for conventional CNC machine tools are the geometric error motions of the individual machine elements, and the thermal errors which cause these geometric errors to change over time. Although the thermal effects are known to be significant, consideration of their effects will be included in a future study.

Geometric error modeling has received wide attention over the last two decades. Tlusty (1971), Tlusty and Koenigsberger (1971), Hocken (1977, 1980), Schultschik (1977, 1978), Bryan (1982), Donmez (1985), Donmez et al. (1986, 1988), Zhang et al. (1985, 1988), Ferreira and Liu (1986a,b) and others, have reported techniques to model the positioning errors in machine tools. In general, each axis of the machine tool is considered to possess six degrees of freedom of error motion in addition to its nominal motion. The purpose of error modeling is to determine a mapping which relates nominal positions in the workspace to tool point error vectors at that position. For a given class of machines, a generic model may be derived which computes this mapping from knowledge of the geometric error motions of the individual machine axes. In order to make the generic kinematic error model describe a particular machine, the individual geometric components of the errors must be measured for that machine. These measurements are time-consuming and expensive, requiring skilled technicians and costly instrumentation.

Despite numerous demonstrations of greatly improved machine precision through error modeling, measurement and correction, few machine tool users have adopted this technology. There are two primary reasons for this
reluctance. The first is the cost of measuring the individual error motions of each machine axis which are needed to parameterize the kinematic error model. Complete measurement of a three-axis machine may require 24-48 h or more. The second reason is the fragility of the data obtained from the measurement process. Minor crashes, wear and changes in the operating environment can render the data useless, necessitating costly downtime for remeasurement.

The objective of this research is to develop methods which make automatic position error correction of machine tools more cost effective. The authors propose to eliminate the costly process of measurement of individual axis geometric errors by equipping the machine with a touch trigger probe and mounting a physical artifact whose dimensions are precisely known in the machine. The machine uses the touch probe to 'measure' the artifact, in the same manner as a coordinate measuring machine. The difference between the measurements reported by the machine tool, i.e. the axis scale readings at the measured surfaces, and the known dimension of the artifact, is the positional error of the machine at that location. By probing a number of different surfaces and features on the artifact, the tool point positioning error can be determined at selected locations in the workspace of the machine. Using this method, the data collection process can be completely automated, and accomplished in a small fraction of the time required for conventional methods.

In order to software correct the machine errors, the tool point error must be known at arbitrary points in the workspace, not just points corresponding to the artifact features. Therefore, a system for interpolating between the measured points is required. The purpose of this paper is to simulate the use of an artificial neural network (ANN) to accomplish this interpolation. In this application, the ANN uses the nominal coordinates of the cutting tool as inputs and produces the corresponding components of the tool point error vector as outputs. The input-output pairs for the ANN training set are the error vector components at selected locations obtained from machine probing of the artifact.

The results presented in this paper are based on a simulation of the artifact-probing process described above. During a previous research effort sponsored by General Electric, the kinematic error model of a CNC slant bed turning center was derived and the geometric error components were measured. This model, along with the measured error components, is used to compute the probe-positioning errors during the simulated artifact measurement process for a variety of potential artifact geometries. The data set from the simulated measurement is then used to train a neural network. The trained network is tested by having it compute the predicted tool point error at a regular grid of points throughout the workspace, and comparing the predicted error at each point with the actual error obtained from the kinematic error model.

Section 2 describes the modeling of kinematic errors for machine tools. Section 3 describes the neural network architecture and the training procedure. Section 4 compares some possible artifact geometries and the results obtained when each is used to generate the ANN training set. Section 5 presents conclusions.

2. Kinematic model of the machine tool

Figure 1 shows a schematic drawing of a two-axis machine tool. The machine tool is treated as a serial link, open loop, kinematic chain. At one end of the chain is the part being machined, at the other is a cutting tool or a measuring probe. Each joint in this chain possesses one degree of freedom, which is in the intended direction of motion. The actual motion differs slightly from the intended motion. This error motion is a small rigid body motion with six degrees of freedom. It is assumed that

![Fig. 1. A two-axis machine tool.](image)