Development of an Independent Real-time Position Feedback Device for CNC Machining Operations

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1. Introduction

Sandia National Laboratories' (SNL) low volume manufacturing of a highly diversified product line has created new manufacturing and inspection challenges. Statistical process control (SPC) has been utilized in the past at SNL by influencing the manufacturing process based on trends. However, SPC techniques are most useful when applied to high volume manufacturing. With lot sizes decreasing, and product diversity increasing, the desire to eliminate or minimize independent product inspection has grown.

In order to effectively get the product right every time total process control (TPC) methods are being investigated and implemented. Under TPC quality is built into the process, where all attributes influencing the production process are detected, analyzed, and controlled, preferably in real-time. To date, feedback on machine tools and other manufacturing hardware has been limited to sensing motion at often large distances away from the actual point of operation (i.e. – encoders on ball screw or scales adjacent to guideways), sometimes including a volumetric error correction algorithm. Industry and University publications attribute up to 80% of the part errors to thermal and geometric effects and inaccuracies.

In response to the need within SNL for TPC, a novel device for real-time, in-situ measurement of the position of a milling spindle relative to the worktable is currently being developed at SNL under a three-year lab-directed research & development (LDRD) project. This new measuring device is capable of tracking and providing real-time feedback of the position of a milling head relative to the worktable during machining operations, independent from the machine tool's controller and axis feedback systems.

2. Measurement Device Overview

The main design objectives were (1) to build a relatively inexpensive device that was thermally stable, (2) easy to transport, (3) easily adaptable to different machine architectures and (4) yields very precise measurements suitable for feedback for error correction (3µm).

2.1. Design and Construction

The device proposed and constructed is a three revolute joint serial linkage arm (Figure 1). Joints one and two are constructed of Invar for thermal stability and utilize ABEC grade 7 ball bearings for smooth, accurate motion. The joint axes of joints one and two are constructed to be mutually perpendicular and intersecting. Alumina rods 305mm long, selected for their thermal stability and high stiffness to weight ratio, connect joint three to joint two and from joint three to the probe ball. ABEC grade 7 bearings are also used in joint three. The workvolume of the device is approximately a 1.2m diameter sphere.

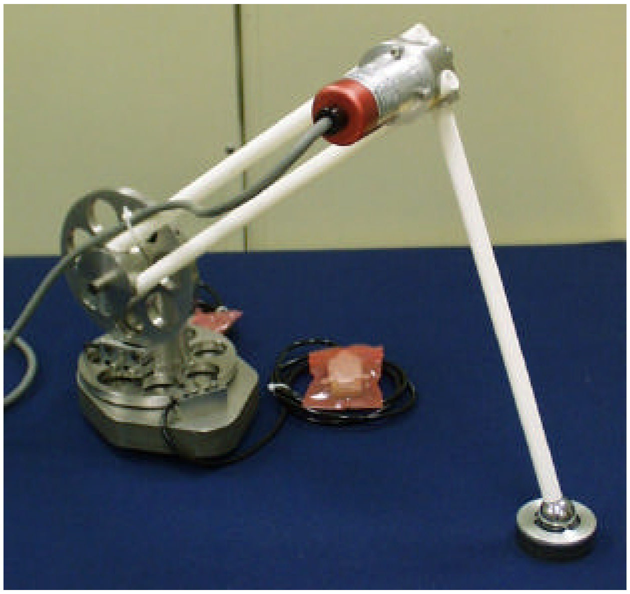

Figure 1 – 3-DOF serial linkage measurement device.

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2.2. Position Feedback System

Two types of encoders were considered for feedback. The first was a SNL built disk encoder made of a Renishaw 0.1µm flexible scale wound around a precision-ground Invar disk, yielding a resolution of 3counts/arcsec. The second was a Canon K-1 with 81,000counts/revolution K-1 using an 80x interpolator yields a resolution of 5counts/arcsec. Extensive testing of repeatability and accuracy of these two encoders referenced to a Zeiss RT05 rotary table (certified 1arcsec accuracy) showed that the SNL encoders were significantly more repeatable than the K-1 (Figure 2). With proper calibration the SNL encoders are expected to exhibit better than 5arcsec accuracy, which is very comparable to the K-1.

In light of the experimental results, the SNL Renishaw scale encoders were chosen for joints one and two. The final grind on the disk periphery and the joint shaft bore for each joint were completed in the same setup and on the machine to minimize form error and radial error motion of the disk relative to the joint axis centerline. The Canon K-1 encoder was chosen to be used on joint three for its compact size and low mass (80g).

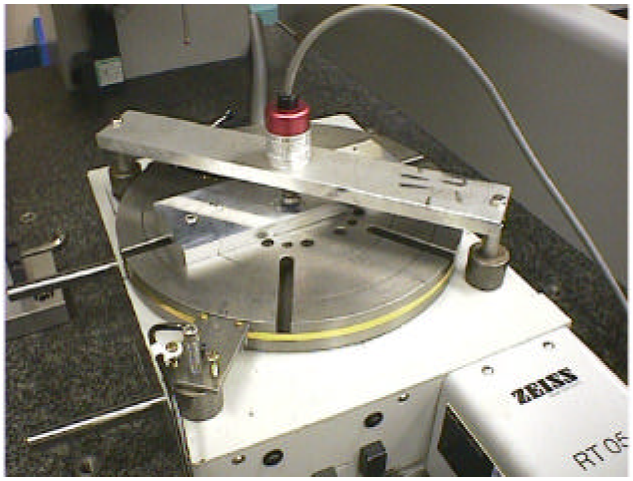

Figure 2 – Experimental test setup of SNL and K-1 encoders versus Zeiss RT05.

3. Proposed Device Implementation

3.1. Machine Tool Metrology Frame

The primary use of the device is as a metrology frame to measure in real-time motion occurring between a point near the tool tip of a milling machine and the coordinate system of the workpiece being manufactured. In this mode the base of the device is connected to the machine tool's table near the workpiece with the probe tip attached to a point on the milling head near spindle nose by a magnetic kinematic coupling (Figure 3). The device is then aligned electronically to the axes of the machine tool. The probe tip then may be disconnected and used to probe the tool and the workpiece blank to establish the geometry of the part and tool setup relative to the metrology frame.

During the execution of a part program, the relative motion of the worktable and milling head are sensed by the device. Positional errors that occur are sensed in-situ, and fed into the control loop of the machine tool for compensation. In this manner, positional errors in the machine tool from thermal or geometric effects may be compensated during motion. It is important to note here that this is a three-DOF measurement device, while there are 21 errors in a three-axis machine tool that combine into six errors between the tool tip and the part frame. Therefore it takes three of these devices to capture all of the errors or at least a second three-axis attachment to capture the rotational errors. Due to budgetary constraints, only one device is currently being built and tested at this time.

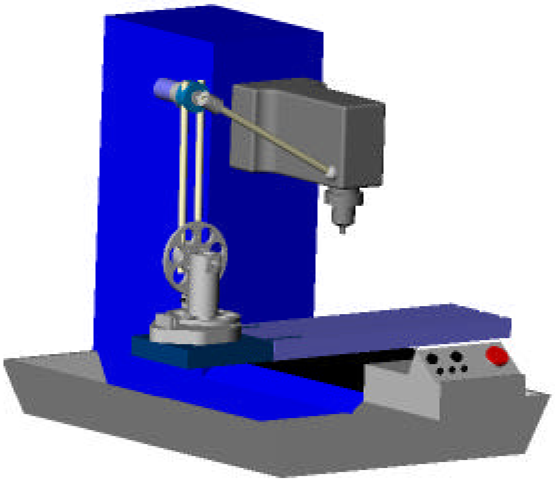

Figure 3 – Conceptual picture of measuring device installed on small milling machine.

3.2. Manual Probing

In addition to part and tool setup and checking on the machine tool (section 3.1), geometric features of a part may be directly measured at particular intervals during pauses in the machining cycle. The probe ball may be detached from the kinematic mount on the machine and used as a manual coordinate measuring machine (CMM). The entire device also may be removed from the machine tool and taken to a surface plate (or other measurement location), where it may be used as a portable CMM.

4. Uncertainty Analysis

4.1. Governing Equation for Position

The equation for the position of the probe center point relative to the base reference frame via a serial linkage is easily determined by Equation 1 from the Devanvit-Hartenburg parameters (DHP) appearing in Table 1. Figure 4 shows the geometrical significance of the DHP on a single link.

$$^{G}P_{Tool} = {}^{G}T_1 \, {}^{1}T_2 \, {}^{2}T_3 \, {}^{3}P_{Tool} \qquad where:$$

$$^{i}T_j = \begin{bmatrix} \cos(q_j) & -\sin(q_j) & 0 & a_{i,j} \\ \sin(q_j)\cos(a_{i,j}) & \cos(q_j)\cos(a_{i,j}) & -\sin(a_{i,j}) & -\sin(a_{i,j})S_j \\ \sin(q_j)\sin(a_{i,j}) & \cos(q_j)\sin(a_{i,j}) & \cos(a_{i,j}) & \cos(a_{i,j})S_j \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

Table 1 – Nominal DHP for measurement device.

Link Length (mm)	Twist Angle (deg)	Offset Distance (mm)	Joint Angle (deg)
$a_{G1}=0$	$\alpha_{G1}=0$	$S_1=123$	θ_1=variable
$a_{12}=0$	$\alpha_{12}=90$	$S_2=0$	θ_2=variable
$a_{23}=305$	$\alpha_{23}=0$	$S_3=0$	θ_3=variable

	$^3x_{tool}$ (mm)	$^3y_{tool}$ (mm)	$^3z_{tool}$ (mm)
$^3P_{tool}$	305	0	0

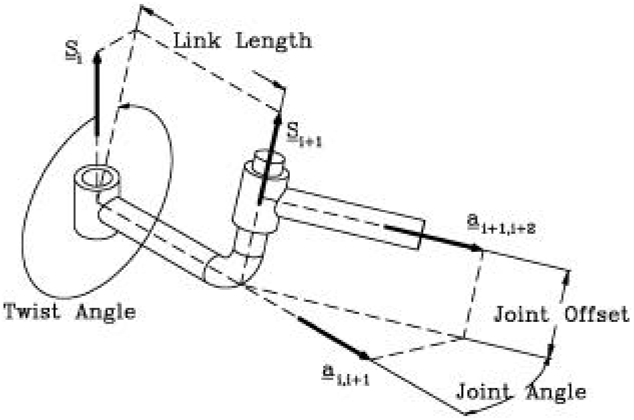

Figure 4 – The DHP are the physical dimensions of a link in a serial chain.

4.2. Error Budget

Uncertainty in the DHP stems from a variety of factors including thermal effects, encoder accuracy and repeatability, imparted mechanical loads, imparted gravitational loads, bearing error motions (radial, face, tilt and motions) and device calibration. A total of 40 factors were considered to contribute to the uncertainty in the 13 DHP for the device. For brevity, only the combined uncertainties in the DHP are shown (Table 2). Interested readers are encouraged to contact the authors for a complete listing of all of the uncertainty contributors.

Table 2 – DHP estimated uncertainties.

Model Parameter	Combined Uncertainty	Units
θ_1	0.000021	rad
S_1	0.003	mm
a_{12}	0.003	mm
α_{12}	0.000022	rad
θ_2	0.000010	rad
S_2	0.003	mm
a_{23}	0.005	mm
α_{23}	0.000022	rad
θ_3	0.000010	rad
S_3	0.003	mm
Ptool3 - X	0.005	mm
Ptool3 - Y	0.002	mm
Ptool3 - Z	0.006	mm

4.3. Uncertainty Calculation and Workspace Mapping

Since the DHP are the basic kinematic parameters of a serial device, they are not inherently cross-coupled. Since the calibration process relies on direct inspection the measured DHP will not become cross-coupled during calibration. Under these circumstances the combined uncertainty at the probe point may be calculated assuming that the effects of the DHP uncertainties act independently from each other and are therefore uncorrelated. In compliance with the ANSI/NCSL *U.S. Guide to the Expression* *of Uncertainty in Measurement,* a type "A" analysis was conducted using the combined uncertainty rule in Equation 2. Where x consists of the DHP.

Using Maple to symbolically derive the 13 partial derivatives of Equation 1 and MATLAB to evaluate them with their respective individual uncertainties, the combined uncertainty occurring at the probe point was evaluated and mapped over device's workspace. From this analysis the maximum combined uncertainty in the reported position of the tool tip is 18µm (Figure 5).

$$u_p = \sqrt{\sum_{i=1}^{13}\left(\frac{\partial P}{\partial x_i} u_{x_i}\right)^2} \tag{2}$$

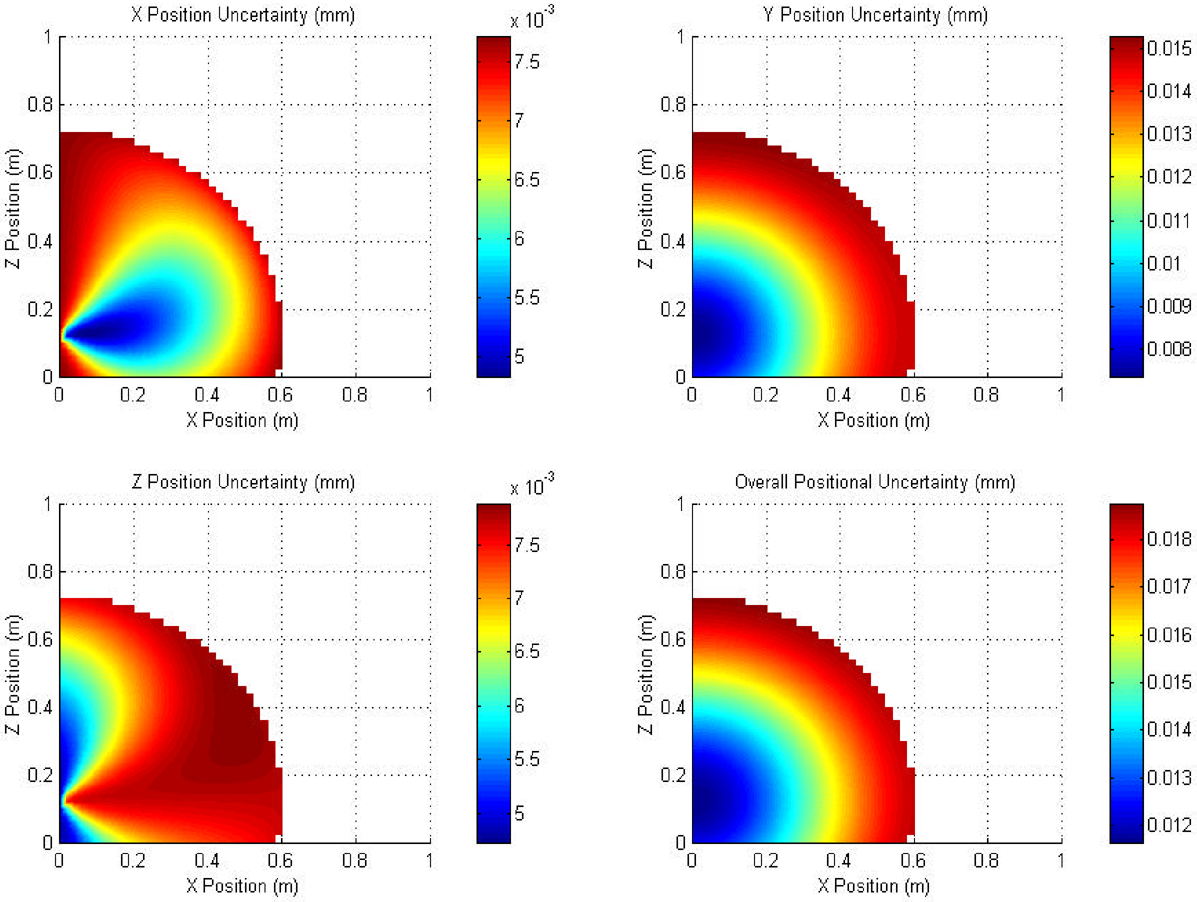

Figure 5 – Combined uncertainty map at probe point.

5. Conclusions and Future Work

A prototype portable and multi-use metrology frame and CMM has been designed and analyzed, and is currently in its final phase of assembly and interfacing. The prototype system will be able to independently measure, feedback, and compensate relative motion measurements occurring between a milling head and part being produced with an uncertainty between 12-18µm. Recent improvements in Rensiahw's flexible scale product line to 50nm resolution may also be implemented in which case the uncertainty in the reported position of the probe tip will drop to 10µm. Calibration and testing of the prototype and implementation on a small CNC milling machine is expected to be completed in December.

6. Acknowledgements

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