INTRODUCTION
This paper describes the design and evaluation of two contact probes used to measure the length and bore concentricity of cylindrical, extruded tool joints while clamped in a production lathe spindle. The axisymmetric tool joints, which provide connections between individual drill pipes in the oil industry, are produced using two primary manufacturing processes: the joints are initially extruded and then finish machined. One typical obstacle to optimizing the turning performance is deviations from the nominal dimensions for the extrusions, including length variations and non-concentricity of the inner and outer diameters. This causes more or less material to be removed than commanded during the ensuing turning, boring, and facing operations. If the part is larger than nominal, a conservative machining approach is required to avoid larger depths of cut than commanded and the subsequent potential for tool/part damage and/or accelerated tool wear. A natural alternative to conservative part paths is pre-machining measurement while the parts are chucked or clamped in the machine. Yandayan and Burdekin [1] provide a review of the different methods used to accomplish this task (up to 1996) and Vacharanukul and Mekid [2] continue the survey through 2003. In this study, two LVDT-based contact probes were developed to measure the length and bore concentricity of tool joints while clamped in a lathe spindle in order to provide pre-machining extrusion dimensions. These results can be used to modify the part program in real time.

PROCESS BACKGROUND
Variations in the indirect extrusion process lead to geometric imperfections that affect the turning process; see Fig. 1. First, as the material flows up and around the pin during extrusion, a bulge can be created at the end; the bulge peak is not necessarily located at the midpoint between the inner and outer diameters. Second, length variations occur due to fluctuations in the part temperature (a high-temperature shearing operation precedes the extrusion process). Third, after many extrusion cycles, the pin may both: 1) begin the extrusion off-center with respect to the container centerline; and 2) lose its parallelism to the container axis during extrusion. The combination of these issues generates parts with length variation, non-flat ends, and non-concentric bores (with non-constant concentricity along the bore length). The extruded parts are machined on Okuma LC-40 lathes, which include two independent turrets. The upper turret (A) is used to perform boring and drilling operations on the extrusions, while the lower turret (B) is used for facing and turning cuts. The turrets enable relative motion between the part and tool in both the z (parallel to the spindle centerline) and x (diametral) directions.

FIGURE 1. Indirect extrusion process.
the extrusion face in the z direction. However, the latter two measurements required contact with the (inner) bore diameter. Because it was inconvenient to align the LVDT axis in the x direction within the bore (based on LVDT sizes and the bore diameter), a design was required that would transfer motion along the surface normal of the inside diameter to the z direction, where it was convenient to orient the LVDT axis. A parallelogram leaf-type flexure and 45 deg surface were chosen to accomplish this task. Figure 2 demonstrates the design concept where x displacement of the platform caused by variation in the surface location is transferred to the z direction via the 45 deg surface.

Figure 2. One-to-one ratio between x direction surface location and z direction shaft motion.

The depths of cut for roughing passes are up to 5.1 mm. A 1% error in the commanded depth of cut is therefore 51 µm. Assuming that this 1% error is an acceptable variation in the actual depth of cut, the target uncertainty for the two probes was set to 50 µm.

**Length Probe**

It was determined that side (lateral) loading of the LVDT resulted in poor transducer performance. Therefore, a shaft supported by linear ball bearings was incorporated to resist the inherent side loading from the rough extrusion surface and transfer only axial motion to the LVDT. Figure 3 shows the design, where the 12.7 mm diameter shaft is constrained using two linear ball bearings (to increase lateral stiffness) and the LVDT is supported by two collars inside a 2024 aluminum tube (310.4 mm length). This ensures that both the shaft and LVDT share (nominally) the same motion axis. A 440C hardened stainless steel sphere is fixed to the end of the shaft; this sphere serves as the contact surface during measurements. The shaft is spring-preloaded against the part during measurements (see the collar and 720 N/m spring at the left end of the assembly). The LVDT is preloaded against the shaft using its own internal spring. The probe is mounted in turret A using a boring bar holder. This ensures that the probe axis is (nominally) coincident with the z axis with a zero offset in the x direction.

**Concentricity Probe**

Figure 4 shows the concentricity probe design. As noted previously, this design includes a flexure and 45 deg surface to transfer the x direction bore surface location to the z direction (and the LVDT axis). The flexure platform carries a 12.7 mm diameter 440C hardened stainless steel sphere to provide contact with the bore surface. As the part rotates, the radial variation in the surface location causes the platform to be deflected in the x direction. This motion is transferred to the z axis through the 45 deg machined surface on the platform (the flexure was designed such that parasitic motion is negligible [3]). A shaft supported by linear bearings is again used to isolate the LVDT from side loads. A second sphere (9.5 mm diameter, grade 24, Rockwell C58-C65) is attached to the shaft which maintains contact with the 45 deg surface; preload is supplied by a spring/collar. To reduce friction and abrasion at the 45 deg surface, a thin glass sheet was epoxied to the 45 deg surface.

**MEASUREMENT PROCEDURES**

**Length Probe**

Once the probe was mounted in the boring bar holder on turret A, an initial calibration constant,
was determined to compensate for any misalignment during assembly. Turret A was then used to position the probe against the part backstop located inside the chuck; the backstop provides a hard stop for inserting extrusions in the spindle collet chuck. The turret’s z coordinate was then recorded as $z_{ref}$ and the corresponding LVDT mean voltage was recorded as $V_{ref}$.

The presence of the part backstop provided a convenient reference surface for transforming the LVDT displacements into part dimensions with values larger than the LVDT range. The approach was to use the machine position (as reported by the controller) for macro-scale motion between the backstop and the unclamped end of the part. By combining the change in the z axis value with the difference in LVDT voltages when touching the backstop and part face, the length could be determined.

Once the reference location was identified, a part was chucked in the lathe and the probe was placed in contact with the part face near the part’s outer diameter. This turret z location was recorded as $z_{meas}$. Ten measurements were completed at equally spaced x locations from the outer to inner diameter. Since the voltage decreased as the LVDT pin was depressed, the machine x value associated with the lowest voltage identified the location where the bulge was largest (for this radial location). The turret x value was recorded as $x_{peak}$ for this position.

The next step was a continuous measurement around the face of the part at the $x_{peak}$ radial location. The part was rotated at 18 rpm while the voltage was recorded at 5 kHz for 15 seconds (to capture multiple revolutions). After applying a Butterworth low pass filter with a 5 Hz cutoff frequency and isolating a single revolution of data, the lowest voltage, $V_{meas}$, was used to calculate the part’s maximum length. See Eq. 1.

$$L = \left( z_{meas} - z_{ref} \right) - \left( \frac{V_{meas} - V_{ref}}{K_L} \right)$$  \hspace{1cm} (1)

**Concentricity probe**

A similar process was used for the concentricity probe. However, because a diametric reference surface was not available on the lathe, an artifact, with known diameter, $D$, was used to determine the probe’s calibration constant, $K_C$, and reference values, $V_{ref}$ and $x_{ref}$. Part measurements were completed by placing the probe in contact with the inner bore diameter at the desired depth. The $x_{meas}$ axis location was recorded and then data was collected during rotation of the part, filtered, and one revolution was isolated. For subsequent measurement at other depths, the spindle was returned to (ideally) the same orientation before beginning data collection.

The LVDT voltage recorded during part rotation provided information about both the hole radius and the offset of its center from the spindle axis, which was assumed to coincide with the part’s axis of rotation defined by its outer diameter. Figure 5 shows an exaggerated representation of the measurement as the part rotates counterclockwise. The outer circle represents the part’s outer diameter, while the smaller solid circle represents the off-center bore. As the part rotates, the bore center traces the smaller dashed circle. The center offset, $o$, is the distance from the spindle axis to the bore center. The bore radius, $r$, is the perpendicular distance from the bore center to the surface of the inner diameter. Note, however, that the probe measures x displacement only, not part radius.

$$2r - 2D = \frac{K_C V_{meas} - V_{ref}}{x_{ref}}$$  \hspace{1cm} (2)
Given the sinusoidal filtered output, $x$, of the sensor as a function of angle of rotation, $\theta$, both the radius and bore center offset from the spindle axis at the selected $z$ location along the bore can be calculated. The radius is the mean value and the offset is the difference between the maximum and minimum values divided by two. The variation in the bore center location is determined by comparing the results from different $z$ locations. The phase shift for the maximum $x$ was used in conjunction with Eqs. 3 and 4 to determine the coordinates of the bore center location, $x_c$ and $y_c$, for the selected $z$ depth inside the bore.

$$x_c = o \cos(\Delta \theta) \quad (3)$$

$$y_c = o \sin(\Delta \theta) \quad (4)$$

RESULTS
In order to verify the probe's performance, measurements of the artifact using the length and concentricity probes were compared to dimensions obtained using a coordinate measuring machine (CMM) in Table 1. The probe values show reasonable agreement with CMM results. Although the disagreement is larger than the two-standard deviation uncertainty in the CMM measurements ($2 \times 0.012 = 0.024$ mm) for the radius measurement, the results are acceptable for this application. Note that the length probe algorithm identifies the maximum length of the part. For any chucking error (i.e., if the part axis is not parallel to spindle axis after clamping), the length probe measurement will therefore give a result which is larger than the actual part length.

<table>
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<th>TABLE 1. Artifact measurement results.</th>
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<td>CMM result (mm)</td>
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<td>-----------------</td>
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<tr>
<td>$L$</td>
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Repeated length measurements were performed on a single part (without removing it from the spindle) in order to establish the length probe measurement repeatability. Five length measurements were completed. The resulting lengths were {521.272, 521.269, 521.266, 521.266, and 521.264} mm. The range is 0.008 mm with a standard deviation of 0.003 mm.

Similarly, repeated measurements were completed using the concentricity probe. A single part was measured five times each at four axial locations without unclamping the spindle chuck. The range of variation for the center offset and radius was 0.005 mm or less for all five locations. The center location was less repeatable, but this is to be expected since the spindle angular orientation could not be reset to the same starting point between measurements (no spindle encoder access was available).

To evaluate the influence of chucking repeatability, the same part used for the length measurements was removed from the spindle and then re-clamped. The difference in measured length for multiple parts was approximately 0.200 mm. Using the radial error motion at the part surface taken with a dial indicator ($\pm 0.61$ mm to $\pm 2.2$ mm) and the part geometry, each time a part is chucked there is a potential for a $\Delta L$ change in length of 0.182 mm to 0.653 mm. This range encompasses the variation in the on-machine length measurements and verifies that clamping non-repeatability is a significant contributor to part length deviation.

CONCLUSIONS
In this study, two contact probes were designed, fabricated, and implemented to measure the length and bore concentricity of cylindrical, extruded tool joints while clamped in a production lathe spindle. Given the pre-machining part dimensions, a selection could be made from a pre-defined matrix of part programs that are defined using the anticipated range of part dimensions. The part program would be selected such that depths of cut that are significantly larger than expected (based on nominal part dimensions) would be avoided. In this way, the time-consuming approach of defining the part program based on the largest possible part would be replaced and the cycle time and machining cost would be reduced while increasing the tool life.

REFERENCES