ABSTRACT

FURST, STEPHEN JOSEPH. Automatic Handling Technology for Precision Turning of Two-Sided Parts. (Under the direction of Dr. Thomas A. Dow.)

The fabrication of precision two-sided artifacts is a difficult, time-consuming task. Both sides of such artifacts need to be precision turned on a lathe. Two separate chucks are required to hold the part during machining of the inner contour (IC) and outer contour (OC). Currently, a skilled operator is needed to transfer the part from one chuck to another. To ensure that reference surfaces on both sides are correctly oriented on the machining chuck, the operator must realign the part by measuring run-out with a gage and tapping the part into place.

The goal of this study is to develop an automatic transfer and realignment process for a part on a dual-spindle machining center. A hemispherical shell is chosen for demonstration because hemispheres lack “self-aligning” features, and thus require the most complex handling capability.

At the moment of transfer, it is desired to have the axial separation between the part and receiving chuck no less than 125 μm (0.005”). Also, the radial gap between an ideal part and the receiving chuck should vary by less than 8 μm (0.0003”), meaning the radial misalignment between the hemispherical part and spindle centerlines is less than 4 μm. A transfer procedure was developed and demonstrated at the Precision Engineering Center (PEC). The demonstration showed that at the moment of part transfer, the radial misalignment between the part surface and receiving pot chuck was less than 1.5 μm (60μin. ) and the axial position of the part will have an uncertainty of 5 μm.

In addition to the transfer procedure, a method was developed to realign the part in the event that radial run-out occurs during transfer. This method involves measuring the magnitude and direction of the radial run-out with either a touch probe mounted to the machine slides or an analog electronic gage. The part is then tapped in the appropriate direction by a mass
driven with a voice coil until the part and spindle centerlines are within 5 µm (0.0002”) of each other. A procedure was developed to employ this actuator in part realignment. This procedure was successful in repeatedly repositioned a hemispherical part with an initial run-out of 1-2.5 mm (0.3-1”) to within 5 µm of the spindle centerline. This capability shows that the run-out of a part manually placed on a OC chuck or transferred from an IC chuck to an OC chuck can be corrected.
Automatic Handling Technology for Precision Turning of Two-Sided Parts

by
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Stephen Furst was raised in Goshen, NY – about 60 miles Northwest of New York City. He graduated high-school in 2003 and came to NC State University to study Aerospace Engineering and compete on the University Track and Cross Country teams. During the summer of 2006, Stephen conducted research on Lunar Science at the NASA Langley Research Center, while helping to develop a Senior Design project for which he was a team leader the following year. After graduating Summa Cum Laude in Aerospace Engineering in May of 2007, Stephen spent the summer working on Raman Spectroscopy and robotics at the NASA Ames Research Center. The following fall, Stephen began work on Automatic Handling Technology for Precision Two-Sided Parts under the direction of Dr. Thomas Dow at the NC State University Precision Engineering Center.
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1 Introduction

1.1 Background

One of the most significant challenges in manufacturing precision two-sided objects is the alignment of the surfaces on opposing sides of the part. Diamond turning lathes are capable of producing single-sided parts with form accuracy better than $\lambda/10$ (60 nm) [1]. However, machining both the inner and outer diameters of an artifact such as a hemishell and maintaining an alignment error of less than 5 $\mu$m (0.0002”) is a complicated endeavor. A two-sided part such as a hemishell must be transferred from one chuck designed for IC (Inner Contour) machining to another chuck designed for OC (Outer Contour) machining. This transfer process is usually done by a skilled operator who is responsible for removing the part from one chuck, then replacing and realigning the part on a second chuck. Typically an operator can position a part to within 5 $\mu$m of the spindle centerline. However, eliminating manual part transfer and alignment operations can reduce the total human effort and exposure during the manufacturing process. The result will be a significant cost savings and improved part accuracy.

1.2 Automated Part Transfer

The first objective of this project is to become the first study that develops the capability to measure a hemispheric artifact on-machine then transfer that artifact to a precisely known location. This technology will be applicable to new, multi-spindle machining centers (e.g., Mazak Integrex series). A measurement system is needed to verify that the size of the part is appropriate for the receiving chuck. It must also ensure that the axial gap between the part and the chuck is not less than 125 $\mu$m (0.005”) at transfer, and that the variation of the radial gap between the part OC and IC chuck at transfer is less than 8 $\mu$m (0.0003”). This means that if a hemispherical part is assumed to be perfectly round, its centerline must be less than 4 $\mu$m from the centerline of the opposing IC (pot) chuck during transfer.
Figure 1 shows a test artifact as well as the vacuum chucks required for OC and IC machining. It also shows a touch probe, which could be used to locate the part and chuck surfaces so that the transfer can be completed without human intervention. The fiducial reference surfaces on both chucks are indicated.

**Figure 1:** Hemishell and Vacuum Chucks for Two-Sided Diamond Turning

The transfer procedure has been developed in the context of the NCSU Precision Engineering Center (PEC) diamond turning machine (DTM), which differs from the multi-spindle machining centers for which this technology was intended. A multi-spindle machining center has two opposing spindles, while the PEC DTM only has one spindle. Also, most multi-spindle lathes have a multi-axis probing stage in addition to a two degree-of-freedom tooling axis—the PEC machine has only a two degree-of-freedom stage. As a result of these differences, some of the steps required at the PEC will not be necessary when the process is implemented on more advanced machining centers.

### 1.3 Run-out Correction

During the IC to OC transfer process, radial run-out may cause a misalignment between the part and spindle centerlines. Currently, a skilled operator is needed to push or tap the part
back into alignment. However, a second objective of this study is to develop a method for automatically measuring the radial run-out and realigning the part on the vacuum chuck. The goal is to correct part run-out initially as large as 2.5 mm to within 5 µm (0.0002”) The capability to realign a run-out as large as 2.5 mm will enable the system to correct errors from two different sources: run-out resulting from the IC to OC transfer, and run-out that results when a part has been manually placed on the OC Chuck for initial machining.

The behavior of the friction force, which holds a part on a vacuum chuck, is pivotal to the development of the realignment technique. Many researchers have characterized the behavior of friction for a variety of applications [2-10]. Olsson et al. summarize the an array of friction models, which include discussion of static, Striebeck, Coulomb, and viscous friction, as well as more complex friction models, such as Daul’s model, that are used for precision controls applications [4]. Static, Striebeck, Coulomb, and viscous models describe friction force as a non-linear function of velocity. Daul’s model, like models presented by Haessig, Canudas and Futami, attempt to explain the behavior of the friction interface prior to slipping [5-8]. They suggest that the interface behaves as if the two surfaces are coated with asperities that act like springs, allowing two surfaces to displace slightly under a force that is lower than static friction. When observed, this behavior is especially important in describing friction on the micrometer scale.

Previous work has also been attempted that applies friction models specifically to actuation against friction and automated part alignment [11-20]. Mears discussed the alignment of a part against friction and a tapping method of actuation [12]. His work was based on a vertical rotary stage, where the normal force is generated entirely by the weight of the part. Like Mears, Siebenhaar also actuates a part on a vertical stage; however, he uses an impulse generated by an electromagnet [13]. The system presented in this thesis, unlike Mears’ and Siebenhaar’s works, is based on a horizontal spindle, where the normal force to friction is provided by vacuum and may be 100 times the weight of the part. Huang and Mason attempt controlled impulse manipulation by tapping a part and using position feedback to ensure that
the part approaches a desired position [15, 16]. Huang also endeavors to prove the controllability of a micropositioning system using three separate tapping actuators on the same part [17], while Suyama et. al. employs tapping controlled by fuzzy reasoning and feedback from an eddy current probe to position a part within ±2 µm of a desired position [18]. Others have attempted to align parts using high frequency, low amplitude vibrations generated by piezoelectric actuators [14, 19, 20].

While these researchers have endeavored to position a part held in place by friction, their methods are only applicable for a short range and small friction force. Many of their methods require precise positioning of the realignment actuator. This thesis develops a new, long-range actuator that can automate the precision alignment process. The alignment method can be used for two applications: realigning a part that has been automatically transferred from one holding fixture to another and centering a part that has been manually placed on a spindle for initial machining.

2 Sensor Selection

A part location and measurement system is needed to make both the automated part transfer and realignment goals possible. For example, the transfer of an artifact from one holding fixture (chuck) to another requires that the positions of both fixtures and the part be known in the same coordinate system. A sensor is needed to locate these three components, which are shown in Figure 1.

Locating the three components in Figure 1, both axially and radially about the spindle centerline, requires a probe that can sense a surface from a variety of directions. For example, the perpendicular axial and radial fiducial surfaces in Figure 1 must both be located, and it is essential to locate both with the same sensor. This requires a sensor that is capable of measuring accurately and precisely over very long ranges (i.e. several cm). However, since the location of only a few points on the part and fixtures are needed to
reference the components, this sensor does not need to be capable of capturing high frequency dynamics or locating a large number of points in a short period of time.

The second sensing application is the measurement of the radial run-out of a misaligned part on a spindle, as shown in Figure 2. This sensor can be capable of operating over a much shorter range than the sensor used for the part transfer (~3 mm); however, it should be capable of locating at least 10 points on the part surface in a reasonably short period of time. In a typical run-out measurement, the part would be rotated on the spindle and a sensor would measure the variation in the radial distance between the part surface and the spindle centerline.

![Figure 2: Misaligned Part on a Spindle](image)

The sections below describe a number of sensing probes. Capacitance gages, LVDT’s, and touch probes are considered and their strengths and weaknesses are discussed. Finally, probes are chosen for the different applications based on these comparisons.

### 2.1 Capacitance Gages

Capacitance gages work by measuring the capacitance between two conducting surfaces. One of the conducting surfaces is typically on the gage, while the other is on the part surface.
A standard capacitance gage is only capable of measuring along one axis—the axis normal to the conducting plate on the gage. Some different configurations are shown in Figure 3.

![Lion Capacitance Probe Geometries](image)

**Figure 3:** Lion Capacitance Probe Geometries [21]

Although a single measurement axis will be insufficient for locating points on the surface of a sphere or on perpendicular faces of a holding fixture, a set of gauging surfaces could be arranged in a cluster, as shown in Figure 4.

![Capacitance Gage Cluster](image)

**Figure 4:** Capacitance Gage Cluster

It is also possible to use a spherical gauging surface, as shown in Figure 5. This single surface could detect a surface of interest from any direction, but it would be incapable of determining the direction from which the surface of interest is approaching. Only one voltage will be output, and that voltage will tell the operator that there is another conductor within range.
A spherical probing head would also add complication because the plates of the “capacitor” would not necessarily be parallel. For example a spherical probing head in proximity to a convex conductor would produce a different output voltage than a spherical probing head in proximity to a flat or concave conductor, as shown in Figure 6.

While a capacitance gage with a spherical head could effectively detect a part approaching from many different directions, the complexity of programming a single trigger voltage is a drawback. Also, although a capacitance gage can have a resolution better than 50 nm, they measure over a range of less than 100 µm. Finally, the variable nature of the sensitivity between different shaped conductors made a capacitance gage undesirable for both sensing applications in this project.
2.2 **LVDT**

Linear Variable Differential Transformers (LVDT), like the capacitance gages, are capable of measuring displacement in a single direction. In an LVDT, an alternating current in the primary coil, labeled A in Figure 7, induces a variable magnetic field in the ferrous core which translates along the measurement axis. This variable magnetic field in turn induces a voltage in a pair of secondary coils, labeled B in Figure 7. Generally, displacement is linearly related to the output voltage from the secondary coils.

![Figure 7: Cross-Section of an LVDT [22]](image)

The core of an LVDT slides on plastic, a roller, or a frictionless air-bearing and offers a longer measurement range than a capacitance gage—up to several centimeters, with sensitivity better than 0.1% of the measurement range.

An electronic gage such as a shaded-pole inductor operates under the same principle as the LVDT. The probing head of an electronic gage is attached to a friction-adjustable pivot. Both a friction pivot and air bearing, shown in Figure 8, help ensure that contact forces are low so that the part is not damaged or deflected during probing.
Figure 8: LVDT Probe Designs for Measuring the Shape and Run-out of Parts on Spindles

Despite their single measurement axis and ability to measure relative displacements only, LVDT and electronic gages are well suited for measuring part run-out. As an off-center part is rotated on a spindle, an LVDT will show a maximum displacement when in contact with the high side of the part and a minimum when contacting the low side. However, the single measurement axis makes determining an absolute dimension such as the diameter of a sphere extremely difficult for an LVDT or electronic gage. Unless the probe were accurately referenced to the spindle centerline, the probe would have to detect one side of the part then rotate 180 degrees to locate the opposite side of the part, while somehow maintaining its frame of reference.

LVDT and electronic gages are used extensively in this project in setup and alignment steps, as well as in the radial run-out measurement. However, because they can only sense along one dimension they are not suitable for measuring and locating the hemisphere prior to transfer.

2.3 Touch Probes

Kinematic touch probes have been used on coordinate measuring machines since patented by McMurtry in 1979 [23]. A typical Renishaw probe configuration is shown in Figure 9. When the spherical head of a touch probe contacts the object it is measuring, the contact
force causes the probe’s stylus and three pivots to rotate. When one or two of the electrical contacts, labeled 2 in Figure 9, opens, the electrical circuit is broken. The opening of the circuit acts as the triggering signal for the probe. The contacts are preloaded via a spring, labeled 3 in Figure 9. The force on the probe tip that triggers the measurement can come from any direction around a hemisphere above the probe tip. This is an improvement over the other probes discussed above, which are only effective at locating a surface from one direction. Touch probes can be triggered from different directions, then use the position of the machine axis to which the probe is mounted as a measurement scale.

**Figure 9:** Renishaw Touch Trigger Probe [24]

In trade for their omni-directional detection capabilities, touch probe measurements have substantially lower resolution than LVDT’s and cap gages. Additionally, touch probes introduce many error sources. For example, prior to probe triggering, a small rigid body rotation must take place. Additionally, the stylus will bend as a result of the triggering force. The stylus deflection and rigid body rotation combine to form an effect known as pre-travel—the distance the probe head moves before the probe triggers. Pre-travel varies with the direction of contact, in an effect known as lobing. Fortunately, a touch probe can be calibrated to remove much of the pre-travel error.
Also, a touch probe by itself is not capable of measuring distance—the probe simply produces a trigger signal when it contacts a surface. To be useful on a machining center, the probe must be fixed to the machine axes. The probe touch acts as a trigger to record the position of the machine axes. Then multiple points can easily be references within the same coordinate system. Typical diamond turning machine axes have laser interferometer feedback with an accuracy and resolution of a few nm. However, using the machine scale as a reference makes it necessary to move a heavy machine axis in order to move the probing head and measure different points. This makes it difficult for a touch probe mounted to a machine axis to locate more than a few points per minute, thus making the probe useless for measuring high frequency dynamics.

Despite the low bandwidth of a touch probe mounted on a machine axis, the omni-directional location capability and range as long as the machine axes range (15-20 cm) makes a calibrated touch probe ideal for locating points on the part and fixtures prior to part transfer.

### 2.4 Sensor Selection Summary

To summarize, a calibrated touch probe mounted on a DTM stage can be used to locate a surface from almost any direction with a resolution better than 1 µm, while allowing for substantial over-travel. When mounted to a machining stage with laser interferometer positioning control, a touch probe can be typically used over the range of the stage—usually greater than 10 cm—without degrading the resolution. However, touch probes in this arrangement are only capable of locating one point every few seconds. Nevertheless, the touch probe is used to locate the part and fixtures prior to transfer. It is also available as an option for the run-out measurement.

LVDT, electronic gages, and capacitance gages offer a shorter range of measurement with higher resolution, and they can be easily damaged if they are forced to move out of range. However, their high bandwidth and self-contained measurement scale make long range electronic gages useful for run-out measurement as well as many setup and alignment steps.
3 Touch Probe Errors and Calibration

The errors associated with measurements taken by a touch trigger probe will be discussed in this section, with reference to the coordinate system shown in Figure 10.

3.1 Three Dimensional Lobing

When the applied trigger force originates from different $\Phi$ directions, the pre-travel distance varies predictably in a phenomenon known as lobing. This is because the magnitude of the force and rigid body rotation required to open one of the electrical contacts varies depending on the location of the pivots. For example, if a trigger force $F_2$ in Figure 11 is applied, the stylus will pivot about the bottom two supports, and the moment arm that will open the contact at the top support is very long. As a result, only a small rotation is required to trigger the probe. The opposite is true for a contact originating from $F_1$, where a larger rotation is required to trigger the probe.

![Figure 10: Touch Probe Coordinate System](image)
Figure 11: Touch Probe Pivots

Figure 12 shows the variation of pre-travel with $\Phi$, as determined by Dobosz and Wozniak [25] for a Renishaw TP6 probe, which was used for the experiments. A trigger from the direction of $F_1$ requires a greater rotation and thus a greater force, so a larger stylus deflection will result. The diagram in Figure 12 captures all of these errors, along with errors caused by the probe ball having geometry that differs slightly from a perfect sphere.

Figure 12: 2-D Touch Probe Lobing

For the measurements in the transfer procedure, the effects of traditional lobing caused by variation in $\Phi$ only partly describe the errors. For this project the trigger force direction will
vary exclusively in the \( \theta \) direction. Prior studies on the 3-D error compensation for a slightly different touch probe have been done by Estler [26, 27]. Estler’s model and measured pre-travel are shown in Figure 13. Estler used a precision calibration sphere to determine his measured pre-travel data. In Figure 13, each block of 120 on the “Point Index” represents a full rotation of 360 degrees in \( \Phi \). The different 120 point blocks then represent an interval of 10 degrees in the \( \theta \) direction. The block of point indices between 360 and 480 represents the lobing around the equator of the probe head (\( \theta = 0 \) as defined in Figure 10). The data in this block, although plotted differently, contains the same information as the data in Figure 12. The data between point index of 1440 and 1560 represents repeated touches on the “South Pole” of the probe head (ie. \( \theta = 90 \) degrees from Figure 10).

Figure 13: 3D Pre-Travel for TP-2 Touch Probe [26]

3.2 Trigger Signal Noise

Another source of error in a touch probe is trigger signal noise. If a 5V input voltage is applied to the touch probe, the untriggered probe will produce an output voltage of 5V. Ideally, once an electrical contact is broken, the output voltage goes immediately to zero and
stays there. However, in reality, the probe’s output voltage takes time to equilibrate after a trigger in a process known as “probe bounce.” The machine axis will be constantly in motion while the probe is triggered, so it is important for the machine coordinates to be recorded at the exact moment that the probe is first triggered. The update rate on the PEC’s DTM controller, which records both the axis positions and the probe output, is 800 Hz. Therefore, if the axis and probe are moving at a rate of 0.2 mm/min when the probe is triggered, there will be a maximum uncertainty of 4 nm (0.16 µin.)—the distance the probe head moves between controller cycles. This is calculated in Equation (1), below

\[
\frac{0.2\text{mm}}{60\text{sec}} \frac{1\text{sec}}{800\text{cycles}} \Rightarrow 4\text{ nm cycle} \tag{1}
\]

This ideal level of precision will not be attainable if the probe triggers erratically or repeatedly at a single point. Therefore, a signal conditioning unit is used to smooth the output of the touch probe into a clean square wave. The signal conditioner used is the Renishaw MI-9. The MI-9 inputs and outputs are labeled in the block diagram in Appendix A.

### 3.3 Touch Probe Trigger Repeatability

Trigger repeatability is defined as \(2\sigma\) of the trigger location for multiple touches at the same angle on the same object. Since a centered calibration sphere can be touched for reference prior to any measurements, the primary error source becomes trigger repeatability. For this application, the touch probe only needs to find points along a 90 degree arc, therefore the 90 degree section of the probe with the best trigger repeatability will be used for measurement.

The trigger repeatability is found by touching the calibration sphere in Figure 14 from 13 different radial vectors, shown in Figure 15, below. These vectors represent a change in the angle \(\theta\) only, where \(\theta\) is defined in Figure 10. The measurements are repeated 10 times, and the standard deviation, \(\sigma\), of the radius measured from each vector is calculated using Equation (2).
Figure 14: Reference Sphere used for Touch Probe Calibration

Figure 15: Calibration Sphere Touch Vectors

\[ \sigma = \sqrt{\frac{\sum (r - \bar{r})^2}{n - 1}} \]  \hspace{1cm} (2)

The probe is then rotated in \( \Phi \) and the touches in Figure 15 are once again repeated 10 times. The results from three different \( \Phi \) orientations are plotted in Figure 16 and Figure 17.
Figure 16: $2\sigma$ Trigger Repeatability from Calibration Sphere

Figure 17: Close Up of $2\sigma$ Trigger Repeatability from Calibration Sphere

Figure 17 shows that the lowest $2\sigma$ of trigger repeatability occurred between 270 and 360 degrees in orientation 1. The spindle center line is not being crossed during measurement, and the part will only be touched on one side. Therefore, it is only necessary to use a 90 degree range of trigger vectors. Accordingly, it is best to use the portion of the probe that has the best repeatability. The maximum $2\sigma$ between 270 and 360 degrees in orientation 1 is 0.27 μm (10.6 μin.). For each touch of the probe, the error is a combination of this trigger
repeatability and the calibration sphere’s maximum departure from perfect geometry, 63.5 nm (2.5 µin.). The two errors are combined as shown in Equation (3).

\[ e = \sqrt{0.270^2 + 0.064^2} = 0.277 \mu m \]  

(3)

This error must accompany any measurement taken using the touch probe. Since it represents the 2σ trigger repeatability, 96% of all data points taken should fall within 0.277 µm of the value on the axis at the moment of trigger. Note that the transfer is being tested on a Rank Pneumo ASG 2500 diamond turning machine with laser interferometer feedback on the axis position. The axis position resolution is 2.5 nm (0.1 µin.), a negligible source of error.

3.4 Touch Probe Calibration

When determining the diameter and center location of a spherical object on the spindle, it is necessary to touch at least three points, which can be limited to a 90 degree arc on both the hemisphere and probe head. If the part is replaced with a precision sphere, all of the errors from pre-travel variation and probe head ball geometry can be determined. Through compensation those errors are eliminated, leaving only the sum of the precision sphere geometry variation (63.5 nm) and trigger repeatability (280 nm) as errors.

Once the chucks are aligned and the probes placed in their final orientation, the pre-travel errors can be corrected by touching each point on the calibration sphere that correlates to the points to be touched on the hemisphere. With the chucks aligned, the touches in Figure 18 will locate the z origin, find the x coordinate of the apex (of both the calibration sphere and the part), and calibrate for pre-travel at the design touch points, shown in Figure 18.
To be able to calibrate the pre-travel effects, the radius of the calibration sphere needs to be known precisely, as does the separation between the center of the calibration sphere and the center of the part, labeled $Z_C$ in Figure 18. The radius of the ball is 12.69937 mm (0.499975”) with an uncertainty of 64 nm (2.5 µin.), and $Z_C$ is 51.4497 mm (2.02556”) with an uncertainty of 280 nm (11.2 µin.), the trigger repeatability.

The correlating touch points on the hemispherical part are labeled 3, 4, and 5 in Figure 19, below. Henceforth, the coordinates of 3, 4, and 5 on the calibration sphere in Figure 18 will be labeled with the subscripts cal_3, cal_4, and cal_5.
The calibration factors for measurements taken at each of the touch points labeled in Figure 19 are listed in Equation (4) through Equation (9). These calibration factors must be added to each set of coordinates recorded when the probe triggers at the labeled locations. This will allow the locations of the points to be properly compared so that relative distances can be determined. Note also that a touch on a calibration sphere that is in a known location serves to reference the touch probe to the machine coordinate system. The touches on points 1 and 2 in Figure 18 also serve this purpose, so they only need to be used as a check.

\[ x_3 = -x_{cal_3} - 12.69937 \]  
\[ z_3 = 0 \]  
\[ x_4 = -x_{cal_4} - 12.69937 \sin 45 \]  
\[ z_4 = -(z_{cal_4} - z_c) + 12.69937 \cos 45 \]  
\[ x_5 = 0 \]  
\[ z_5 = -(z_{cal_5} - z_c) + 12.69937 \]
4 Hemispherical Part Transfer

The transfer procedure is designed to find and measure a part on one chuck, find the opposing chuck within the same coordinate system, and transfer the part from one chuck to the other. The axial separation between the part and the opposing chuck must be at least 125 μm (0.005”), according to the system requirements. Additionally, the radial gap must be uniform to within 8 μm (0.0003”). Since it is assumed that the part is a perfectly round hemisphere for the transfer process, a radial gap uniformity of less than 8 μm means that the part and spindle centerlines are separated by less than 4 μm at the moment of transfer.

To make the required measurements, it is necessary to provide a frame of reference and locate all of the parts and probes with respect to that frame of reference. All of the relevant
components are shown in Figure 20. As pictured, the part is located on the chuck used to machine its outer diameter (the OC Chuck). The IC Chuck and the touch probe are both fixed on the PEC DTM’s x-slide and oppose the OC Chuck and hemisphere part. The points labeled 1 through 5 represent the locations where the touch probe should contact the hemisphere and fixture to fully define the location of the part. The purpose of each touch is outlined in Table 1. An air-bearing LVDT is rigidly mounted to the spindle housing and is used for the initial alignment only. Note also that the step of the OC Chuck is machined with a smaller diameter than the hemispherical part. This exposes the back of the part, which can be used to measure the motion of the part during transfer.

Table 1: Touch Point Descriptions

<table>
<thead>
<tr>
<th>Point Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Radial Reference Surface</td>
</tr>
<tr>
<td>2</td>
<td>Axial (Z) Reference Surface</td>
</tr>
<tr>
<td>3</td>
<td>Point Near Part Equator</td>
</tr>
<tr>
<td>4</td>
<td>Arbitrary Touch Point on Part</td>
</tr>
<tr>
<td>5</td>
<td>Part Apex</td>
</tr>
</tbody>
</table>

Basic Transfer Procedure

Any part transfer will involve the following basic setup and measurement steps. Each step is discussed in subsequent sections.

1) Initial alignment of the two opposing spindles.
2) Locating the touch probe.
3) Determine the size and location of the hemisphere part.
4) Locate the center of the hemisphere part.
5) Locate the opposing chuck in the same coordinate system as the hemisphere part.
6) Calculate the coordinates for vacuum chuck transfer.
7) Move to the transfer coordinates and switch the vacuum.
4.1 Initial Alignment

On the PEC DTM, a setup step is required to align the spindle, which holds the OC Chuck, with the IC Chuck, which sits on the x slide and is an analog to the second spindle on a dual-spindle machining center. This is done by attaching a Federal gage to the spindle, and setting it in contact with one of the radial surfaces of the IC Chuck, as pictured in Figure 21. When the spindle is rotated, the Federal gage will indicate the magnitude and direction of the misalignment.

![Figure 21: Radial Alignment of IC Chuck and Spindle](image)

A similar process is used to set the front face of the IC Chuck parallel to the x-y plane, but the Federal gage is reoriented to measure the face run-out instead of the radial run-out, as

![Figure 22: Alignment of IC Chuck Face](image)
shown in Figure 22. Once the chucks are aligned to within approximately ±1.5 μm (0.00006”), the relative x coordinate system is set to zero in the DTM controller. The x alignment need only be performed once for any machine setup, so long as the chucks are secured. The x origin is set when the OC Chuck and IC Chuck are radially aligned.

### 4.2 Locating the Touch Probe

Once the two simulated spindles are aligned, the touch probe must locate a reference surface so that the probe can then be used to locate the part. In reality, the reference location can be chosen anywhere, because it is the position of one component with respect to another that is important for the transfer. However, for simplicity of discussion, the z origin is taken as the point where the probe head center is in the same plane as the equator face of the part. This point is found by touching the fiducial face of the OC Chuck, point 2 in Figure 20. The thickness of the ledge separating point 2 and the face that contacts the part equator is known to be 5.4189 mm from previous measurements. A probe touch on point 2 can be used to place the center of the touch probe head in z and set the relative coordinate system to zero.

A caliper is used to set the location of the touch probe in y by measuring the height of the probe head above the stage. The y position of the spindle centerline and the radius of the touch probe head are known. The caliper is placed on the stage, and set at the spindle height plus the probe head radius. The probe is then moved toward the caliper’s reference edge until the probe triggers. Although calipers are relatively inaccurate, y centering error does not contribute significantly to more critical x and z errors. This is discussed further in Section 4.6.

After the z origin is set as described above, the location of the touch probe with respect to the OC Chuck is known. To locate the probe with respect to the spindle centerline, all that is needed is a probe touch at point 1 in Figure 20, because the radius of the OC Chuck is known (see Section 4.5).
At this point the location of the IC Chuck with respect to the OC Chuck in x is known, as is the location of the touch probe with respect to the OC Chuck in both x and z. To determine the relative locations of the two chucks in z, it is necessary to find the location of the touch probe with respect to the IC Chuck in z. That is, the offset between the touch probe head and the IC Chuck face, shown in Figure 23, must be determined. On the PEC DTM, the probe is fixed on an axis with no rotational degree of freedom. As a result, the touch probe offset must be measured through an alternate method which employs an air-bearing Linear Variable Differential Transformer (LVDT), mounted as shown in Figure 20.

The air bearing LVDT is aligned with the touch probe in x and y by sweeping the touch probe with the LVDT along both the x and y axes. When the LVDT’s displacement is at a maximum, the spherical heads of the LVDT and touch probe are aligned. This maximum displacement value is then recorded, along with the z axis position of the LVDT body, labeled $Z_{\text{probe}}$ in Figure 23. The LVDT body is then moved until the gage is in contact with the IC Chuck face, and the LVDT’s displacement matches the maximum displacement previously recorded. The z position of the body, now $Z_{\text{chuck}}$, is recorded again. The difference between $Z_{\text{probe}}$ and $Z_{\text{chuck}}$ is the z separation between the probe head and the IC Chuck.

![Figure 23: Touch Probe/IC Chuck Location in Z](image_url)
With the touch probe located with respect to the IC Chuck, it is now possible to locate the part with respect to the IC Chuck by simply touching the OC Chuck or the part apex with the touch probe.

Also note that the touch probe was only subjected to a small force when located by the LVDT; however, when the touch probe is triggered on the part apex it undergoes pre-travel prior to triggering. This pre-travel distance, discussed in Section 3, must be added to the $z$-separation dimension.

### 4.3 Part Measurement and Location

After the touch probe and chuck are aligned and located, the LVDT may be removed from the setup. At this point, the system is ready to measure a hemispherical part that has recently been machined on the OC Chuck. The touch probe touches it at the equator, the apex, and a point halfway between, denoted by points 3, 5, and 4 in Figure 20. Using these three points, it is possible to determine the radius and center point of the sphere using the method to be described in Section 4.3.1. If the measurements prove that the part is neither too big nor too small to fit in the spherical IC Chuck (pot chuck), then the transfer can proceed. In using this method, it is necessary to assume that the shape of the recently machined part is close to a sphere.

#### 4.3.1 Hemisphere Measurement

Once a part is machined on the OC Chuck, it needs to be measured using the machine axes and touch probe. This measurement will answer three questions:

1) Was the part machined correctly?
2) Will the part fit in the IC (pot) Chuck?
3) How far does the part need to move before the vacuum supply can be switched to the receiving fixture and the transfer can be made?
Three Point Method

The three point method determines the radius and center point of a circle that includes any three non-collinear points: \((x_1, y_1), (x_2, y_2),\) and \((x_3, y_3)\). The equation of this circle can be written in the form of Equation (10).

\[
\begin{vmatrix}
X^2 + Y^2 & X & Y & 1 \\
x_1^2 + y_1^2 & x_1 & y_1 & 1 \\
x_2^2 + y_2^2 & x_2 & y_2 & 1 \\
x_3^2 + y_3^2 & x_3 & y_3 & 1 \\
\end{vmatrix} = 0
\]  

(10)

Solving the determinant in Equation (10) produces Equation (11).

\[
X^2 + Y^2 + 2dX + 2eY + f = 0
\]  

(11)

From Equation (11), the center \(\left(-d, -e\right)\) and the radius \(\sqrt{d^2 + e^2 - f}\), where \(d, e,\) and \(f\) are defined in Equations (12), (13), and (14).

\[
d := \left(\frac{1}{2} \left( y_3^2 x_2 - y_3^2 y_1 + x_3^2 y_2 - x_3^2 y_1 - y_2^2 y_3 + y_2^2 y_1 - x_2^2 y_3 + x_2^2 y_1 + y_1^2 y_3 - y_1^2 y_2 + x_1^2 y_3 - x_1^2 y_2 \right) \right) / \left( -x_3 y_2 + x_3 y_1 - x_2 y_3 - x_1 y_3 + x_1 y_2 \right)
\]  

(12)

\[
e := \frac{1}{2} \left( -y_1^2 x_3 - x_1^2 x_3 + x_1^2 x_2 - x_2^2 x_1 + x_2^2 x_3 + x_3^2 x_1 - x_3^2 x_2 + y_2^2 x_1 - y_2^2 x_2 + y_2^2 x_3 \right) / \left( -x_3 y_2 + x_3 y_1 - x_2 y_3 - x_1 y_3 + x_1 y_2 \right)
\]  

(13)
The three circle method assumes a part is a sphere. The radius measurement determines whether the sphere will fit in the pot chuck and whether there have been any gross errors in the machining of the OC. However, it will not allow an operator to discern tool centering errors, because tool centering errors cause the final part to be something other than a sphere, such as an ogive. If the part is not a sphere, the center point calculation will be askew, and the radius measured will not actually be indicative of the size of the part. Fortunately, the location of points 3 and 5 in Figure 18 will tell the operator whether or not the part, which is symmetric about the spindle centerline, will fit in the receiving pot chuck.

### Errors in Three Point Method

When the three point method is used to measure a part, the errors from the trigger repeatability associated with each point are magnified. Figure 24 shows how an uncertainty of 0.28 µm (11 µin.) at each of the three points on a perfect sphere could indicate that the part has the radius indicated by the dotted line, which is smaller than the actual radius by 1.6 µm (63 µin.). The same measurement could indicate a radius 1.6 µm larger than the actual radius. Also, the 0.28 µm error at each touch point could skew the location of the center point by up to 1.4 µm (55 µin.) in any direction. As long as the tool is well centered and these errors are still acceptable, the three circle method can be used to measure a part on the machine, without adding any additional steps to the transfer procedure. Since the size of the part can be measured to within 1.6 µm, it will be possible to determine whether the part will fit in the receiving chuck. The 1.4 µm uncertainty in the center-point location measurement contributes to uncertainty in the alignment of the part and spindle centerlines, which must be within 4 µm during transfer.
4.4 Part Transfer Coordinates

If the part is determined to be of proper size, the transfer coordinates can be determined from the z location of the hemisphere apex, point 5 in Figure 20. The x coordinate for transfer is 0, set during the initial spindle centerline alignment, and the z coordinate is determined from Equation (15). With the exception of Z_5 and pretravel, the terms in Equation (15) are identified in Figure 23. Z_5 is the z location of the part apex, and pretravel is the distance that the probe must move before triggering, as determined in the calibration procedure. Since the pot is short of a full hemisphere, the variable S (shown in Figure 23) is also needed.

\[ Z_{\text{transfer}} = Z_5 - (Z_{\text{probe}} - Z_{\text{chuck}}) - r_p + S + \text{pretravel} \]  

Using these transfer coordinates will place the apex of the shell in contact with the bottom of the pot chuck. If a small gap is desired, then the size of the gap must be added to the \( Z_{\text{transfer}} \) coordinate. The final transfer is made by moving the part to the transfer coordinates, then providing vacuum to the pot chuck and removing the vacuum from the OC Chuck.
4.5 **IC Chuck Measurement**

Equation (15) shows that the IC (pot) chuck must be measured as a setup step for the automated transfer. The pot chuck was measured using the Brown and Sharpe Coordinate Measuring Machine (CMM) at the PEC. The radius and center-point of the pot were determined by touching 15 points on the pot’s radius with the touch probe, then using the CMM’s software to calculate the dimensions. The planar face of the chuck was then touched at 5 places, and the CMM software was used to calculate the position of the plane with respect to the center point. Each measurement was repeated 10 times. The radius was found to be 76.1666 mm (2.9987\)” with a 2σ uncertainty of 1.9 µm (0.00075\)”), and the pot was found to be short of a full sphere by 6.1062 mm with a 2σ uncertainty of 2.1 µm (0.00083\”), as shown in Figure 25. Note that 2σ uncertainty represents a 96% confidence interval, while σ, the standard deviation, is defined as Type A Standard Uncertainty by the U.S. Guide of the Uncertainty in Measurement [28].

![Figure 25: IC (Pot) Chuck Dimensions](image)

4.6 **Error Assessment for Part Transfer**

All of the error sources discussed thus far have created uncertainty in the value of individual measurements. Next, the uncertainties of individual measurements need to be considered in the context of a transfer move. This combines the errors from the initial alignment and the measurements into errors in the x, y, and z position at the moment of transfer. The x and y
errors contribute to radial misalignment, while z errors contribute to uncertainty in axial position of the part with respect to the receiving chuck. The setup and coordinate system are shown in Figure 26.

**Figure 26: Transfer Setup and Coordinate System**

**X Error**

The position of the x-slide required for transfer was set at \( x = 0 \) when the spindle and the IC Chuck were aligned in the first step of the transfer procedure. The location of the origin has not changed throughout the measurement process, and the position of the DTM axis is repeatable to a negligibly small 10 nm. Therefore, the only error that needs to be considered for the x transfer coordinate is the initial alignment error. The alignment of the spindle and the IC Chuck was measured by fixing a Federal gage to the spindle and then rotating the spindle. The radial run-out measurement varied by ±1.5 µm (60 µin.). From this measurement, it is determined that the magnitude of the x-error of the transfer coordinate position is 1.5 µm. When this procedure is implemented in production, the two spindles do not need to be aligned to within 1.5 µm. In a machining station with two spindles, the spindles must be aligned to at most 4 µm to ensure that the variation in radial separation (between a perfect hemisphere and perfect pot chuck) at transfer is less than the required 8
μm. Since measurement errors from the three-point method (Section 4.3.1) also figure into variation in radial separation, the spindle centerlines should actually be within 3 μm of each other. Also, part form errors contribute to variation in radial separation; however, this contribution is ignored in this analysis.

Y Error
After the initial alignment, the y positions of the OC Chuck, IC Chuck, and part remain constant. Therefore, the only y error in the transfer coordinates is the initial alignment error, which is equal to the 1.5 μm (60 μin.) x error. The spindles were aligned in both x and y simultaneously by rotating the Federal gage about the spindle center line, so their errors were indistinguishable, and thus taken to be the maximum run-out magnitude of 1.5 μm.

The touch probe is centered with the spindle center line in y by using calipers to measure the height of the probe head above the slide. The relatively poor accuracy and resolution of the calipers produces an error in touch probe centering of 50 μm (0.002”). While this dimension itself is meaningless for the determination of y transfer coordinates, it does translate into small errors in the crucial x and z measurements. Figure 27 shows how a y-misalignment, d, leads to an error, e, in all of the x measurements made on the sphere.

The calculations in Equation (16) show that the error in all x (and z) measurements on the surface of a 76.2 mm (3”) sphere due to a 50 μm (0.002”) y misalignment is only 17 nm (0.67 μin.). An error of this magnitude can be ignored.

\[
e = R - R' = \sqrt{R^2 - d^2} = \sqrt{76200^2 - 50^2} = 76199.983 \mu m
\]

(16)

\[
e = 76200 - 76199.983 = 17 \text{nm}
\]
Z Error

The uncertainty of the z transfer coordinate must include the errors from all of the terms of Equation (15), as well as the initial alignment errors. The initial alignment resulted in a pot chuck face alignment error that was identical to the radial run-out error of 1.5 µm (59 µin.). The OC Chuck radius and shortness (d in Figure 25) uncertainties of 1.9 µm (75 µin.) and 2.1 µm (83 µin.) from Section 4.4 must also be considered, along with the error from touch probe trigger repeatability of 0.28 µm (Section 3) from the touch at the shell apex labeled 5 in Figure 20. The total error is taken by the square root of the sum of the squares of the individual errors, calculated to be 3.2 µm (0.00013") in Equation (17).

\[
Z_{error} = \sqrt{1.5^2 + 1.9^2 + 2.1^2 + 0.28^2} = 3.2 \mu m
\]  
(17)

4.7 Transfer Summary

A procedure for automating the measurement of a hemispherical part along with its transfer from an OC Chuck to IC Chuck will reduce the human effort required in the production of many different types of two-sided objects. The system described includes both setup steps, which must be executed one time on each machine, along with measurement and transfer steps that must be repeated for each part. The setup, measurement, and transfer steps are
enumerated below. Many of these steps may only apply to the NCSU ASG 2500 machining station, which has a single spindle and two translation axes.

4.7.1 Setup Steps

1) Measure dimensions of OC and IC Chucks on CMM.
2) Align OC and IC Chucks (i.e. align the opposing spindle centerline on a dual machine) by rotating an electronic gage on the spindle.*
3) Mount touch probe and roughly align (50 µm) with the spindle center line in y.*
4) Use air-bearing LVDT to crown the touch probe head in x and y and find the high spot, then determine the touch probe’s offset from the IC Chuck face in z.*
5) Touch the OC Chuck’s fiducial radius and face with the touch probe to find probe’s position with respect to the spindle centerline in x and the hemisphere’s equator in z.
6) Center a calibration sphere on the spindle and touch it at the design points.

4.7.2 Measurement and Transfer Steps

1) Assume a part has been machined and is centered on the OC Chuck.
2) Touch the part in three places—near its equator, at 45 degrees latitude, and at the apex.
3) Check the size of the part to ensure it will fit in the pot chuck.
4) Calculate the coordinates for transfer based on the position of the probe and hemisphere’s apex point, along with the IC Chuck geometry.
5) Move to the transfer coordinates and switch vacuum from the OC to the IC Chuck to complete the transfer.*

4.8 System Demonstration

The setup, measurement, and transfer steps were carried out on the PEC’s Rank Pneumo ASG 2500 Diamond Turning Machine. The DTM’s axis ranges of 150 mm (5.9”) in z and 250 mm (9.8”) in x and axis position resolution of 2.5 nm (0.1 µin.) were sufficient for

* - Step may not be required on a dual-spindle machining center.
collecting the needed data points. The fiducial surfaces on both chucks were machined on the DTM, as was the hemispherical part used in the demonstration. The IC Chuck (pot chuck) radius was cut 50 μm (0.002”) larger than the part-transfer artifact profile.

The z transfer coordinates were calculated such that the part and chuck would have a programmed axial gap of 3 μm when the vacuum was transferred. Then the steps in Section 4.7 were demonstrated. The vacuum was switched and the transfer completed as planned. The transfer was then repeated with the axial gap of set to 125 μm (0.005”), which represents the desired transfer offset requirement. This transfer was also successful. Figure 28 shows the OC Chuck (left), shell, and IC Chuck (right) at three stages during the transfer.

![Shell on OC Chuck](image1.png) ![Shell at Transfer Coords.](image2.png) ![Shell in IC Chuck](image3.png)

**Figure 28:** Hemisphere Part Transfer Steps

The position of shell with respect to the pot chuck at the transfer coordinates was determined through the initial alignments and the measurements. The predicted maximum error of the actual position of the shell at transfer from Section 4.6 is tabulated in Table 2 below.

<table>
<thead>
<tr>
<th>Error (μm)</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error (μm)</td>
<td>1.5</td>
<td>1.5</td>
<td>3.2</td>
</tr>
</tbody>
</table>

As shown in Figure 20, the back of the part is accessible and can be used to measure its displacement during the transfer process. A Federal gage was used to measure this motion.
The expected motion of the part was the planned separation of 3 µm plus the Z error from Table 2 of 3.2 µm, which combine to make 6.2 µm. A displacement of 8 µm (315 µin.)—about 2 µm larger than expected—was measured. Since this displacement was measured at only one point on the back of the part, rotation during transfer could account for the small discrepancy. The minimum separation desired is much larger (125 µm or 0.005″) so the 2 µm difference is negligible.

By using the calibrated touch probe the radius and center-point position of the hemispherical part can be determined with an uncertainty of 1.6 µm (63 µin.) and 1.4 µm (55 µin.), respectively. The initial radial (x and y) alignment error of 1.5 µm and the 1.4 µm center-point uncertainty contribute to variation in radial separation between the hemispheric part and pot chuck. Taking the square root of the sum of the squares of the initial alignment and center-point errors indicates that a point on the surface of an ideal sphere could be up to 2.5 µm (98 µin.) from its nominal location. This figure ensures that the centerlines of the part and pot chuck were separated by less than 4 µm (150 µin.) at transfer, as required. Since the pot chuck was machined to be 50 µm (0.002″) larger than the part, the pre-transfer measurement will be sufficient to ensure the part will fit in the chuck.

Radial run-out of up to 50 µm was observed during the IC to OC transfer system demo. Since a pot chuck is machined to be larger than the finished part, the part has some room to fall downward during the moment that the vacuum is switched. A larger axial separation at the moment of transfer allows a larger possible radial run-out. The technique for measuring and correcting this misalignment is addressed in the next section.
5 Realignment Technique

5.1 Realignment Goals

The goals for realignment are twofold. First, the realignment technique should correct small run-out errors that occur during the IC to OC Chuck transfer. Second, the realignment technique should correct larger radial misalignments of up to 2.5 mm (0.1”) resulting from manual placement of the part on the chuck. The realignment technique should be autonomous and position the center-point of the hemispherical part within 5 µm (200 µin.) of the spindle centerline.

5.2 Run-out Measurement

Measurement of the magnitude of the radial run-out and its angular orientation is essential to realignment. Since the touch probe was chosen for the transfer steps, a technique is devised so that the run-out measurement can also be made with a touch probe. However, it is important to note that the run-out measurement must be made on a roughly machined part with form errors of up to ±12.5 µm (0.0005”). This form error can add significant uncertainty to the radius and center-point measurement.

5.2.1 Measurement Method and Uncertainty

There are several methods to find the magnitude and direction of run-out. The accuracy of these methods depends on the deviation of the part from a perfect sphere. The first is the three point method described in Section 4.3. This method can accurately measure parts that have small form errors.

If the part differs significantly from a sphere, a second method which employs more touch points can be used to reduce the uncertainty of the calculated center-point location. In the second method, a best fit sine wave is correlated to the touch points via the algorithm in Appendix F. A sample sinusoid fit to a finite number of touch points is shown in Figure 29.
The amplitude of this sine wave represents the magnitude of the run-out and the phase indicates the angular direction of the high spot.

![Runout profile](image)

**Figure 29:** Touch Points and Best Fit Sinusoid for Run-out Measurement

The form errors of the part \((2\sigma = \pm 12.5 \, \mu m)\) and the repeatability errors of the probe \((2\sigma = \pm 0.3 \, \mu m)\) cause each touch point to be offset from the nominal part radius. When a finite number of touch points are used, these errors result in uncertainty in the measurement of the amplitude of the best fit sine (run-out). Touching more points reduces this uncertainty.

The question then becomes: how many touch points are needed to estimate the location of the nominal circle center with sufficient confidence? The number of points needed is determined by simulating touch points and errors using MATLAB. A circle of radius 70 mm \((2.76\text{"})\) is plotted to represent a planar section of a perfect sphere. Touch points are evenly distributed around the circle. At each point, a radial error is randomly selected, and added to the radial coordinate of the original point. This error point represents the location of a touch probe trigger. Since these errors come mostly from the \(\pm 12.5 \, \mu m\) part form error, the random errors are normally distributed about the nominal circle, with \(2\sigma\) equal to 12.5 \(\mu m\). With this distribution, 96\% of the randomly selected points will be within \(\pm 12.5 \, \mu m\) of the nominal location. Figure 30 shows 9 touch points evenly distributed around a circle along with the magnitude of the randomly selected radial error associated with each point. The best fit
circle of the errors is taken to find the measured radius and center-point location. The location of the high spot is indicated by the dotted vector. In this case, the high spot is only the result of sampling error, since the nominal circle is actually centered at the origin (i.e. the part has zero run-out).

**Figure 30:** Chosen Touch Points and Randomly Generated Radial Errors

In the case shown in Figure 30, the center of the best fit circle is offset from the exact center by 2.85 µm (112 µin.) at an angle of 172 degrees. Each time this measurement is repeated a different center offset magnitude and direction is generated, because the randomly chosen errors are different. By repeating this calculation 10,000 times, an estimate of the standard deviation of the center offset error can be calculated.

**Figure 31:** Hemishell Center-Point Location Uncertainty for Simulated Part
Figure 31 shows that touching more points decreases the standard deviation of the center offset error. For normally distributed form and probe measurement errors, the uncertainty of the run-out measurement will approach zero as the number of points approaches infinity. This 2σ standard deviation represents the uncertainty of a run-out measurement.

This measurement method was repeated on a diamond turned sphere which is known to have a 3 Hz frequency form error of ± 5 μm. The measurement was repeated 8 times using 3, 6, and 9 touch points. A measurement was also repeated using 6000 points taken with an analog gage.

**Table 3: Run-out Measurement Uncertainty for a Real Part**

<table>
<thead>
<tr>
<th>Touch Pts.</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>6000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74.84</td>
<td>76.35</td>
<td>77.98</td>
<td>76.60</td>
</tr>
<tr>
<td>2</td>
<td>77.07</td>
<td>77.39</td>
<td>77.64</td>
<td>76.56</td>
</tr>
<tr>
<td>3</td>
<td>79.92</td>
<td>77.17</td>
<td>76.66</td>
<td>76.56</td>
</tr>
<tr>
<td>4</td>
<td>83.59</td>
<td>76.28</td>
<td>76.09</td>
<td>76.58</td>
</tr>
<tr>
<td>5</td>
<td>83.42</td>
<td>76.66</td>
<td>76.90</td>
<td>76.59</td>
</tr>
<tr>
<td>6</td>
<td>83.54</td>
<td>77.47</td>
<td>77.61</td>
<td>76.60</td>
</tr>
<tr>
<td>7</td>
<td>81.75</td>
<td>76.48</td>
<td>76.58</td>
<td>76.56</td>
</tr>
<tr>
<td>8</td>
<td>78.51</td>
<td>76.56</td>
<td>77.64</td>
<td>76.60</td>
</tr>
<tr>
<td>Avg</td>
<td>80.33</td>
<td>76.80</td>
<td>77.14</td>
<td>76.58</td>
</tr>
<tr>
<td>2*Stdev</td>
<td>6.62</td>
<td>0.95</td>
<td>1.34</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 3 shows that using three touch points on a part with a 3 Hz form error produces the largest measurement uncertainty, 6.62 μm. Using an analog gage set to collect 6000 data points over the course of one revolution of the part has a measurement uncertainty of only 40 nm. These uncertainties will vary depending on the frequency and amplitude on the form error of the part being measured. The following section shows how the predicted run-out measurement uncertainty in Figure 31 affects the systems ability to position a part.
5.2.2 Actuator Incremental Displacement

The realignment system must place the nominal center of a part within 5 µm (200 µin.) of the spindle centerline. Figure 31 shows that using 15 touch points will result in a run-out measurement uncertainty of 2.9 µm. Therefore, if 15 touch points are used to measure the theoretical part, it is necessary to place the measured center-point to within at most 2.1 µm of the spindle centerline. Figure 32 shows that the 5 µm error budget is made up of a 2.9 µm measurement uncertainty plus 2.1 µm (83 µin.) of leeway. Therefore, 2.1 µm represents half the maximum value of the incremental displacement of the actuator. If 15 touch points are used to measure a part with 25 µm (0.001”) form error, the actuator must be able to move the part with accuracy greater than 4.2 µm (2.1 µm times 2) to ensure that the actual circle center-point is within 5 µm of the spindle centerline.

![Diagram showing circle center-point measurement uncertainty](image)

**Figure 32:** Circle Center-Point Measurement Uncertainty

5.3 Realignment with Friction

Once the magnitude and direction of the radial run-out is determined, the part must be realigned with some sort of actuator. Since friction is the dominant force that keeps a part from moving on a vacuum chuck, the behavior of the friction force must be considered in actuator design.
5.3.1 Friction Models

Substantial work has been done to characterize the highly non-linear phenomenon of friction [2-6, 9, 10]. The nature and origin of the friction force is not perfectly known, but theories exist and the behavior of friction is well characterized. In general, friction force retards motion between two parallel, contacting surfaces. In its simplest form the friction force can be modeled as the product of a friction coefficient, $\mu$, and normal force, $N$, as in Equation (18) [2].

$$F_f = \mu N$$  \hspace{1cm} (18)

However, friction force is much more complicated than this simple relation because the friction coefficient is not constant. Typically the static friction coefficient between two contacting surfaces with no relative velocity is higher than the dynamic friction coefficient, which results when the two surfaces are sliding. The reduction of friction coefficient due to a relative velocity between the two contacting surfaces is known as Coulomb friction [4]. Additionally, on small scales the transition between static and dynamic friction is also of interest.

**Stribeck Friction**

Stribeck friction attempts to describe the behavior of the friction force as a function of velocity, particularly in the transition between static and dynamic friction [4]. Figure 33 shows the different types of friction forcing phenomenon. Stribeck friction is approximated as a smooth curve which connects the static friction force to the dynamic (Coulomb) friction level.
For the purpose of part alignment on a small scale, the relative velocity between the two sliding surfaces—the part and the vacuum chuck face—is small (~10 mm/s). As a result, the effects of viscous friction, which causes friction force to increase at higher velocities as shown in Figure 33, can be ignored. However, for sub-micrometer positioning, it is also important to consider how the friction interface behaves in response to an applied force that is less than the static friction limit.

**Micrometer-Scale Friction and the Asperities Model**

In general, when no translating force is applied to an object, the friction force holding the object in place is zero. When a translating force lower than the static friction limit is applied, the friction force increases to exactly oppose the applied force. Once the applied force goes beyond the static friction limit, the part will begin to slide on a surface and the friction force will decrease as prescribed by Stribeck and Coulomb friction [4]. Additionally, some researchers such as Bowden, Tabor, Dahl, and Haessig [2, 5, 6] have attempted to explain the behavior of the friction interface under an applied translational force that is lower than the static friction limit. The friction interface has been modeled as a series of elastic bristles or asperities which allow the two surfaces to temporarily displace with respect to one another. Figure 34 shows how these asperities can deflect, allowing one surface to move.
Figure 34: Elastic Asperities at the Friction Interface [11]

In Cuttino’s work [29], the asperities model was applied to a rolling ball guide, where the friction interface was a junction between two curved surfaces under Hertzian deflection. The behavior at a rolling ball guide interface from Futami’s work is plotted in Figure 35.

Figure 35: Elastic Behavior of Friction Interface for Rolling Ball Guide [8]

Figure 35 indicates that the strain in the asperities which temporarily reduce force at the friction interface is a displacement dependent phenomenon. This claim is also supported by Park et. al. [30] who show how friction force changes dramatically during velocity reversal, when the strain on the asperities switches from one direction to another. Park recorded the tracking error of a machine tool, and showed in Figure 36 that the magnitude of the tracking error increases dramatically when the direction of velocity is reversed.
Park demonstrates that the time between velocity reversal and maximum positioning error, $t_{\text{max}}$, relates to the slope of the velocity curve, $a_0$, via Equation (19):

$$ t_{\text{max}} \propto \frac{1}{\sqrt{a_0}} $$  \hspace{1cm} (19)

The fact that maximum positioning error occurs more quickly (i.e. $t_{\text{max}}$ is smaller) when the acceleration of the machine axis is larger suggests that the non-linearities in friction force at velocity reversal are generally displacement dependent. A lower acceleration means it will take more time for velocity to transition from the positive direction to negative direction. Accordingly, it will take longer for the strain in the asperities to be released and reversed. It is during this release that the friction force drops significantly causing an increase in tracking error. Since this substantial decrease in friction force due to the reversal of the strain direction takes place over several micro-meters of displacement it must be considered in the design and calibration of the realignment actuator.
5.3.2 Friction Interface Simulation

The motion of a part with an applied translation force and retarding friction force can be simulated. The non-linear behavior of the friction force can be captured using a discreet-time model described next.

Stick-Slip Model

Stick-slip behavior results when a part is pushed across a friction interface by an actuator with some compliance, as diagramed in Figure 37. Note that the compliance spring could also capture the spring-like behavior suggested by the asperities model and sub-micrometer friction [5-8, 11]. The actuator is forced to move at a constant velocity.

![Figure 37: Stick Slip Model Diagram](image)

As the actuator moves towards the part at a constant velocity, the spring compresses and spring force increases linearly, as in Figure 38c. As long as this spring force is less than the static friction limit, the friction force increases to exactly counter the spring force. Once the static friction limit is reached, the part begins to slide. Then the friction force decreases rapidly, as described by Stribeck friction, approximated by Equation (20). The built up spring force propels the part ahead. Once the spring force is relieved to below the friction force, the part will slow and stop completely. The solid heavy line in Figure 38c shows how friction force is exactly the spring force until static friction is reached; then as the part starts to slip friction force decreases until spring force drops below the friction force. At this point the friction force returns to the static friction level as the part slows down. The resulting behavior is described as stick-slip, where the part moves for a time, then stops completely.
before being forced to slip again. The difference between the spring and friction forces in Figure 38c will accelerate the part according to Newton’s Second Law, \( F = ma \).

**Figure 38:** Simulation of Stick Slip Behavior

In the simulation, friction force (Stribeck) varies with velocity, \( v \), according to:
\[ F(v) = N \left( \frac{A}{\exp(bv)} + B \right) \]  

(20)

where A is the difference between the static and dynamic friction coefficients, B is the dynamic friction coefficient, and b is a chosen constant.

Since the actuator is advancing at a constant rate, the spring force will continue to build until the part slips again. This process repeats, and is responsible for phenomena such as brake squeal. The stick slip behavior can be observed in the position and velocity profiles in Figure 38a and Figure 38b. Figure 38b shows that velocity is constant at zero for most of the time that spring force is lower than friction force. When the part jumps ahead, the velocity reaches a maximum at the time just before spring force recoils and becomes less than friction force. Figure 38a shows that the displacement moves along in steps as the part sticks and slips.

These figures clearly show that the non-linear nature of the friction force causes a part being moved against friction to move at a variable rate. This sort of stick-slip behavior is an impediment for precision control.

**Push Testing**

Push testing was done to characterize the behavior of the interface in response to a force that is applied slowly via a constant velocity push. The setup used to measure the motion of a test puck held onto a plate via vacuum is shown in Figure 39.

The puck is mounted on a vacuum plate which can be moved in the x direction. The position of the puck is measured with an electronic gage mounted to the vacuum plate. The position of the plate is measured with a cap gage that is mounted to machine ground. A load cell is placed between the pusher and the part to measure the applied force.
Figure 39: Constant Velocity Push Test Setup

The pusher is fixed during testing, and the vacuum plate slides in the x-direction, thus forcing the puck into the pusher. The stiffness of the axis to which the pusher is mounted causes the applied force to increase linearly as the x-axis is moved in the positive x-direction. In Figure 40, the puck is moved into the pusher but returned before enough force builds up to cause slipping.

Figure 40: Constant Velocity Push Test with No Slipping
Figure 40 shows that as the axis moves into the load cell and pusher, the force exerted on the puck increases. The puck actually follows a trajectory similar to the axis, however, the maximum deflection of the test puck is only about 110 nm (4.3 µin.). This 110 nm deflection, which results from a 32 N (7.2 lbs) applied force, indicates that there may be an interface stiffness of:

\[ k = \frac{F}{\delta} \]  

This stiffness equals 291 N/µm (1.663 lbs/µin.) and may also result from compliance in the spindle onto which the vacuum plate is mounted. When the pusher axis is allowed to continue, the part eventually slips, as shown in Figure 41.

\[ \text{Figure 41: Constant Velocity Push Test with Slipping} \]

Since the push is slowly applied, any inertial forces caused by puck motion are small. Therefore, it is assumed that the pushing force is equal to the friction force. The force line in Figure 41 shows that the friction force reduces as soon as the puck slips. The friction force then remains constant at a value lower than the static friction limit. The part slips in a manner suggested by the stick slip model, but there is not persistent oscillation. During slipping, the puck simply moves in step with the axis. This would suggest that the built up strain in the interface, described by the asperities model, does not release when the actuation
force is reduced. As a result, the spring model shown in Figure 37 is only valid the first time the part is loaded.

**Impulse Model**

Another way to move a part held on a vacuum chuck by friction is to impart an impulse. This is what a machine tool operator does when he taps a part with a rubber or plastic hammer—a large force is applied over a short period of time. During the impact, both the actuator head and the part surface deform, mostly due to Hertzian deflection. For this simplified impulse model, the system is modeled as shown in Figure 42. The applied force is a non-linear function of time, $F(t)$. A Bruel and Kjaer Type 8202 Impact Hammer is used to tap the part and measure the applied force over the duration of the impact. This force profile is then used as the input to the model. Some compliance is built in to allow for the micrometer friction effects described in Section 5.3.

![Impulse Model Diagram](image)

**Figure 42:** Impulse Model Diagram

The model parameters include the stiffness and damping at the part interface. These parameters are chosen to fit the model to data collected through experimentation.

**Dynamic Testing**

Dynamic testing was used to determine the input forces and parameters to be used in the impulse model. The modeled part motion is then compared to the motion observed during experimentation. The experimental setup is shown in Figure 43.
Figure 43: Impulse Testing Experimental Setup

The impact hammer is used to supply the impulse and a cap gage measures the displacement of the puck with respect to the vacuum plate. All of the axes are fixed during testing. The measured output of the impact hammer and cap gage are plotted against the model input and simulated part displacement in Figure 44a and Figure 44b. Several different taps were executed. A best fit sinusoid is used as the input force for the model. The thin lines in Figure 44a represent the sinusoids that were used as force inputs in the simulation, and the bold lines represent the measured output from the impact hammer. In Figure 44b, the thin lines are the simulated puck displacements, while the bold lines are the puck displacements measured with the cap gage.

Figure 44a: Force Profiles of Several Impact Hammer Taps
Figure 44b: Simulated and Measured Puck Displacements Following Taps

The results of impulse modeling show that the stick-slip displacement of a test part due to an applied impulse can be predicted. However, the prediction is only valid over a certain range of slip displacements for a given set of interface conditions.

5.3.3 Effects of Friction Behavior on Actuation

Much has been learned about the friction interface from modeling and testing in Section 5.3.1 and Section 5.3.2. This information can be used in developing the method for positioning a part that is held on a vacuum chuck by friction. The effects of Stribeck and Coulomb friction were both simulated and measured. It is clear that the friction coefficient drops when the part starts slipping. Experiments showed that this effect results in stick-slip behavior, which creates an impediment for precision control and must be considered in designing a positioning actuator. Since the relationship between the dynamic friction coefficient and relative velocity is dependent on the conditions and materials at the interface, a positioning method should be designed to be as robust as possible to changes in friction coefficient. The interface will behave differently if it is contaminated with oil or chips.

The behavior of the friction interface prior to slip was also studied. The sub-micrometer friction effects suggested by the asperities model were not directly observed as expected. Rather, the displacement of the interface caused by an actuation force below the static
friction limit was very small. Therefore, a high interface stiffness was calculated; however, this stiffness was so high that a substantial component of it may actually come from compliance in the machine axis and shearing of the aluminum test puck. The lower interface stiffness predicted by the asperities model was applicable to a study of a ball-screw positioning drive [11], which modeled the elastic deformation of two curved surfaces. One potential explanation of the absence of the interface compliance suggested by the asperities model is that the strain generated in the interface during a tap did not cause the two aluminum surfaces to recoil back to a relaxed state. Rather, the strain stayed in the interface and future forcing in the same direction was not countered with low friction forces over the first few micrometers of displacement. This hypothesis suggests that the effect of the strain of asperities at the interface may still be significant during velocity reversal, which is explored during part actuation tests to be discussed in Section 5.8.

5.4 Candidate Actuation Methods

A number of methods were considered to overcome the friction force holding a part on a vacuum chuck. The chosen method should satisfy the following criteria:

- Best position control
- Most repeatable
- Lowest risk of part damage
- Fastest realignment
- Lowest control effort
- Most robust to changes in the friction interface
- Easiest to implement on Y12 machining station

The methods considered included pushing the part with one of the machine axes, tapping the part to mimic the process currently used by skilled operators, vibrating the chuck to reduce the friction coefficient, and pulsing the vacuum to reduce the normal force.
5.4.1 Pushing

The simplest method for positioning a part on a vacuum chuck is to push it. A pusher could be attached to one of the machine axes as shown in Figure 45.

*Figure 45: Pusher Attached to Machine Axis*

The position of the axis can be controlled precisely, with feedback from a laser interferometer. However, as was seen in Section 5.3.2, compliance in the pushing axis and the pusher itself causes the force on the block to build as the pusher moved into contact with the part. Although the stiffness of the axis and pusher could be easily determined, the exact force required to move the part would change based on the interface conditions, material, and vacuum pressure. As a result, the deflection of the pusher and axis required to achieve the static friction force would be variable. For an automated system, this variation would necessitate an additional sensor.

Also, the stick-slip behavior studied in Section 5.3.2 would create a limit to the minimum distance a part could be moved. For the case plotted in Figure 41, that distance is only about 1.5 µm (60 µin.), which is the magnitude of the rapid displacement that occurs immediately after slipping begins. However, the retarding friction force in the case plotted in Figure 41 is only 33 N (7.42 lbs). The minimum displacement value would change with the friction force. A larger friction force would result in a larger difference between the static and dynamic friction forces, thus increasing the minimum possible displacement.
Another area of concern is the force to which the part and fixtures could be subjected during pushing. If the pusher is misaligned, or the part gets stuck somehow, the machine axes will be capable of producing significant damage. Pushing with the machine axis can subject the part and fixture to the full force of the machine axis.

5.4.2 Tapping

Tapping is the method currently used by skilled operators for precision positioning. A tap generated by an impact from a moving mass will exert an impulse force on a part with a profile similar to Figure 44. The impulse force must exceed the static friction limit at some point for the part to slip and a permanent displacement to result. Most operators control the magnitude of the applied impulse by feel and feedback. An operator can tap the part a few times and observe the displacement measured by an electronic gage. The operator can also get a feel for how hard of a tap will damage the part.

Tapping as a means of precision control is a tried and true method; the drawback is the difficulty in automating a tap. The momentum that must be imparted on a shell to move it would need to be determined. Also, the momentum that would damage a part would need to be determined and set as an operational ceiling. If one could correlate the imparted momentum to a displacement, then an automated system could rapidly repeat the tap as many times as necessary to realign the part.

Other researchers have attempted to automate the precision positioning process through tapping [12-20]. However, many of these experiments deal with parts on a horizontal stage with the weight of the part providing the normal force. For application to the machining station at BWXT-Y12, a chuck with a vertical face and large vacuum forces is used. The large friction forces that result from large vacuum forces will need to be overcome during repositioning.
5.4.3 Vibrating Chuck

Some research has been done which suggests that vibrating a surface a high frequency may reduce the friction coefficient between that surface and another [31-34]. The mechanism responsible for this friction reduction is not entirely clear, but researchers suggest that the vibrations may induce a surface wave, such as is shown in Figure 46, that causes two surfaces to float apart slightly [34].

![Conceptual Surface Wave](image)

**Figure 46:** Conceptual Surface Wave

Vibrating a chuck face is a significant challenge. The chuck will be made of metal and require a very high, ultrasonic frequency vibration to resonate. The only device available for generating high forces at high frequency is piezo-electric actuator. Substantial power amplification is required to drive a piezo actuator, especially at a high frequency. Also, tests with a piezo actuator on a machining center at the PEC show that many natural frequencies can be excited. The axes, spindle, and chuck will all resonate at multiple frequencies. It is unclear whether resonating a spindle repeatedly will have a deleterious effect on its operation.

5.4.4 Pulse Vacuum

Another method considered for realigning the part was to pulse the vacuum, temporarily reducing the friction force enough to allow the part to slip under the force of gravity. The vacuum force would first be reduced, so that the friction force is just enough to hold the part. Then small pulses of air would be inserted and removed at a high frequency so that the part could slip, but then be caught before moving too far.
The complexities in this method are extensive. First, a model of the air flow through the spindle and vacuum chuck would be required to determine the relationship between pressure and time for a given vacuum pump. The ramifications of failure of this method are also substantial. If too much air was added to the vacuum system, the part could be pushed off the chuck. Additionally, this method still has the limitations of the stick-slip phenomenon. Once the part begins to slip, the friction force will reduce. For a vacuum pump capable of pulling 1000 cm³/s, a hemishell with an inner radius of 7 cm (2.76”) will require roughly 0.7 seconds to empty. Even if the vacuum is pulsed about the pressure that will barely hold the part on the vacuum chuck, it is unlikely that the vacuum force could ever be re-established to pull the part back as quickly as an impacting actuator can recoil. The rate at which an actuation force can be applied and removed is essential to precisely controlling the position of a part under friction.

Although pulsing the vacuum alone lacks the controllability or robustness to move a part, there is no reason why the vacuum should not be reduced somewhat while any of the other methods are applied. The typical vacuum pressure used for holding a part during machining is roughly 85 kPa (12.3 psi), while the pressure required to hold a 140 mm (6”) diameter part on the chuck with a 6.35 mm thickness (0.25”) wall thickness is only about 1.5 kPa (0.22 psi). Therefore, the vacuum force could be reduced significantly without risking the part falling off the chuck. It has also been observed over the course of these experiments that when the vacuum force is reduced and a part is manually tapped, a thin-walled part deforms from its spherical shape; however, when the vacuum force is increased again, the part regains its circular profile.

5.5 **Chosen Actuation Method, Tapping**

5.5.1 **Justification**

Regardless of the method chosen, a force that is greater than the static friction limit will need to be applied to move the part. However, once the part starts to slip and the friction force
decreases, the part will accelerate under the same applied actuation force. Therefore, the best positioning control will likely come from a force that exceeds the static friction limit for a short period of time before being removed. This forcing behavior is best realized with a tap, which is equivalent to a static push that is removed quickly.

**Figure 47:** Idealized Force Profiles

Figure 47 shows the idealized force profiles of two separate hammer taps super-imposed with an approximation of the friction force. Once the tap force exceeds the static friction limit the part will start to slip, the friction force will drop, and the difference between the input tap force and the retarding friction force will accelerate the part. The area between the tap force profile and the friction force profile is proportional to the momentum imparted on the part. Even when the peak of the tap force barely exceeds the static friction limit, as in the case of the solid line in Figure 47, there is a non-zero amount of work done on the part. This suggests that there is a minimum distance a part can be moved against the non-linear friction force.

### 5.5.2 Tap Application Method

The method for applying a tap should provide good control of the energy imparted on the impacting element of the actuator. Additionally, since a part could be out of alignment by as
much as 2.5 mm, a long range actuation method should be used. Power consumption and cost should also be considered.

**Piezoelectric Actuator**

A repeated tap could be generated by a piezoelectric stack placed in series with the machining axis as shown in Figure 48.

![Diagram](image)

**Figure 48**: Setup for a Tap Generated by a Piezo-Stack

As the piezo-stack is vibrated, the force applied to the part would oscillate, thus mimicking the force profile of a tap. The peak force would have to exceed the static friction limit, as shown in Figure 49 where the dotted line is the oscillating force from the actuator and the solid line is the static friction limit.

![Graph](image)

**Figure 49**: Conceptual Oscillation of Actuation Force
This effective tap could be repeated at very high frequency and controlled by varying the voltage amplitude applied across the piezo-stack. Yamagata and Higuchi showed that an impact force provided by a piezoelectric element could provide a positioning resolution of 0.1 µm (4 µin.) [20]. However, piezoelectric actuators have stroke limitations of 0.1% of the length of the piezo-stack, which translates reasonably to about 10-50 µm. Therefore, to be effective in correcting misalignments up to 2.5 mm, the piezo-stack would have to sit piggyback on another, longer range actuator. This long-range actuator would need to use feedback from another sensor to position the piezo-stack within 10 µm of the part being aligned.

**Hammer**

Since a hammer is currently used by an operator to apply a tap, it may be best to emulate a hammer tap for the automated system. A hammer could be set up as shown in Figure 50 and use the force of gravity and a rotational moment about the pivot to generate the momentum necessary to move the part.

![Automated Hammer Configuration](image)

**Figure 50:** Automated Hammer Configuration
This configuration would provide a long range and allow good control of imparted momentum. However, if the force of gravity is used to generate the momentum, a large mass or long moment arm would be needed. This setup would add a bulky component that takes up a lot of space on the machining station.

**Linear Actuator**

A linear actuator such as a solenoid or voice coil motor could also be used to apply a controlled tap. A solenoid is an electro-magnet with a translating core. A potential setup for a solenoid is shown in Figure 51.

![Figure 51: Schematic of Linear Solenoid Tapper](image)

Solenoids and voice coil motors (VCM) offer the ability to apply an initial momentum to a core plunger, then release the core from forcing allowing it to maintain its momentum for several centimeters before impacting the part. This means that a solenoid or VCM could simply be put near the part without precise alignment. The core will just continue to slide until it impacts the part and releases its momentum. Also, the core of a solenoid or VCM is accelerated by forces less than 50 N (11.2 lbs) applied over about 1-2 mm of core travel. When the core impacts a part it is decoupled from the axes, so the risk of accidentally subjecting the part to the full force of the machine axis is reduced.

After weighing the strengths and weaknesses of each tapping method, a linear actuator was chosen as the actuator for use in the realignment procedure. Discussions of designs based on both a solenoid and a voice coil motor are included in the following sections.
5.6 Realignment Actuator

5.6.1 Design Goals
A number of specific requirements need to be satisfied in the design of the linear-motor-based tapping actuator. These requirements will ensure that the actuator has the ability to position the part precisely and repeatedly, while limiting the direct exposure of the part to the potentially damaging machine axes. The actuator must be able to:

1. Accelerate the plunger to a speed of 0.5-1.0 m/s.
2. Hold the impact velocity constant for 3 mm of stroke.
3. Keep friction and wear within the actuator to a minimum.
4. Operate under DC power with simple waveforms.
5. Recoil and settle the core without damaging the actuator.
6. Operate at a frequency of at least 2 Hz.
7. Function in a vertical or horizontal orientation.
8. Have total length less than 12.5 cm (5”).

5.6.2 Solenoid Actuator

Design and Testing
A solenoid tapper was designed to provide a proof of concept demonstration. This actuator, pictured in Figure 52, had the capability to accelerate the translating mass of 55 g to a velocity over 1.0 m/s. The translational axis was mounted vertically, as required, and a foam pad was used to dampen the fall of the plunger after impact. A Bruel and Kjaer type 4393 accelerometer was mounted to the base of the plunger and used to determine the velocity of the plunger prior to impact. A Kistler Type 9251A piezoelectric load cell was used to measure the peak impact force.
The plots in Figure 53 show three regions of plunger travel. In region A, the plunger is accelerated as current is passed through the solenoid coils. In region B, no current is
flowing, but friction and gravity cause a roughly uniform deceleration. In region C, the plunger has impacted an artifact and is recoiling.

Recall that one of the design goals was to have a 3 mm range of stroke where velocity is constant. This would typically occur in region B, but friction and gravity cause deceleration. Therefore, velocity in region B is not constant. A second, low amplitude square wave could be used to provide a force to counter the force of gravity and friction. However, the force on the plunger varies greatly with stroke, so a square wave input would produce a variable force as the plunger progresses through the coils. The relationship between the solenoid actuation force and the position of the plunger in the coils is shown in Figure 54.

![Force Profile for and Unloaded Push Type Solenoid](image)

**Figure 54:** Force Profile for and Unloaded Push Type Solenoid [36]

The solenoid testing has shown that a different actuator is needed that can provide a force that is uniform with stroke so that friction and gravity can be countered with a simple waveform input.
5.6.3 Voice Coil Actuator

A voice coil motor (VCM) relies on permanent magnets to establish a magnetic field. A coil of current-carrying wires within that constant magnetic field will experience a force in accordance with Lorentz’s Law, Equation (22) [37]:

\[ \vec{F} = I\vec{L} \times \vec{B} \]  

In Equation (22), \( I \) is the current in a wire, \( \vec{L} \) is a vector with the same direction as the current carrying wire and a magnitude equal to the length of that wire, and \( \vec{B} \) is the magnetic field vector. For a typical VCM, the actuation force will vary somewhat, as shown in Figure 55. This force variation is much less significant than that seen in a solenoid actuator in Figure 54. The VCM is chosen as the actuation method as a result of the more uniform force output.

![Variation of Force with Stroke in a VCM](image)

**Figure 55:** Variation of Force with Stroke in a VCM [38]

**Design**

A VCM-based actuator has been designed to accelerate a translating core to the desired impact velocity then hold the core at that velocity until it impacts the part and produces an actuation force profile. The core travels on a Thomson Precision Steel linear ball bushing, as
shown in Figure 56 and Figure 57. The total length of the actuator is 12.4 cm; all dimensions are shown in Appendix G. The through-holes on the base plate were drilled slightly larger than the bolts that secure the VCM field assembly. This allows the field assembly to be precisely aligned with the coil assembly, translating shaft, and linear ball bushing.

**Figure 56:** Model of Assembled Tapping Actuator

**Figure 57:** Exploded View of VCM Actuator
Testing

The realignment actuator was assembled as designed and tested in the setup in Figure 58. An accelerometer is used to measure the velocity of the translating shaft and coil assembly, and a load cell is used to measure the peak impact force that results from a given impact velocity.

![Test Setup for Voice Coil Motor Actuator](image)

**Figure 58:** Test Setup for Voice Coil Motor Actuator

The impact is generated by the collision between the translating element of the VCM actuator and a stationary load cell. The VCM is driven with the waveform in Figure 59. The high voltage step is used to accelerate the sliding element, while the low voltage step is used to hold the element at a constant velocity against gravity and friction within the ball bushing. This input is multiplied by a gain between 0.4 and 1.0 to control the applied impulse. If frequency is increased, the duty cycle is also increased proportionately.

![Voltage Input for VCM Actuator at 1 Hz](image)

**Figure 59:** Voltage Input for VCM Actuator at 1 Hz
The velocity profile of the translating core during a typical tap is shown in Figure 60. As in Figure 53, region A in Figure 60 represents the acceleration phase of the core and region C represents the behavior of the core following impact. However, in Figure 60 region B is the period when the input voltage is at a constant, low value that produces a force to exactly counter gravity and friction. The VCM actuator is able to maintain a constant velocity during this phase, during which the moving element translates 6 mm. This improved performance was expected because the actuation force of a VCM does not vary as much with stroke as the actuation force of a solenoid.

To test the performance of the VCM, the load cell was tapped while located at 6 different z-positions using 6 different frequencies. Placing the load cell at different z-locations helps to quantify how the impact energy of the translating element varies through the stroke of the actuator. At each position and frequency, the cell was tapped 10 times at 7 different impulse gain factors. The average peak forces are plotted in Figure 61 and Figure 62. Note that Figure 62 is the same as Figure 61 with the viewpoint rotated to be perpendicular with the two horizontal axes.
Figure 61: Peak Impact Force Variation with Operating Conditions

Figure 62: Peak Impact Force Variation

Tests on the VCM-based realignment actuator show that there is a range of 3 mm of stroke between 4 mm and 7 mm where the peak force variation is less than ±3 N. Also, variation in operating frequency between 1 and 6 Hz does not greatly affect performance.
The repeatability of the peak force during 10 impacts at each position/frequency point is quantified by the standard deviation. The largest $2\sigma$ deviation of peak impact force all of the data points taken was less than 2 N. The standard deviation of the peak force for repeated taps at an impulse magnitude of 0.4, 0.6, and 1.0 are shown in Figure 63. From these three images, it is apparent that the impact force uncertainty shows no clear dependence on impact position or frequency.

Figure 63: Standard Deviation of Peak Impact Force for Repeated Impacts with Gain Factors of 0.4, 0.6, and 1.0
Since the uncertainty (2σ) of peak force for each impact is less than 2 N the VCM actuator can produce a peak force with ±5 N uncertainty over a range of 3 mm. This satisfies the design goal of applying a uniform impact force over at least 3 mm of stroke and indicates that the actuator will be capable of realigning a part with 3 mm of run-out.

5.7 Part and Actuator Impact Dynamics

An actuation tap will typically result from an impact between a spherical actuator head and a spherical part. The dynamics of a collision dictate the peak force and stress that exists between the impacting bodies. This collision can be modeled by analyzing the elastic deformation of these two spheres during a Hertzian collision.

5.7.1 Hertzian Deflection

The Hertzian deflection of the tapper head and aluminum part surface causes an applied force to produce a profile similar to those in Figure 47. The deflection of the impacting bodies allows the collision to take place over a finite, non-zero time, and reduce the peak force values.

The basic formulas for an elastic deformation between two spherical bodies are listed in Equations (23)-(27) [39]. Figure 64 defines some of the variables.

![Diagram of Hertzian Collision](image)

**Figure 64:** Diagram of Hertzian Collision
The radius of the impact area, \( a \) is:

\[
a = 0.721 \sqrt{PK_D C_E}
\]  

(23)

The maximum stress over that area of the impact is:

\[
\sigma_{\text{max}} = 1.5 \frac{P}{\pi a^2} = 0.918 \sqrt{\frac{P}{K_D^2 C_E^2}}
\]  

(24)

The change in the distance between the center-points (approach of the centers) of the two impacting spheres throughout the duration of the collision is:

\[
y = 1.040 \sqrt{\frac{P^2 C_E^2}{K_D}}
\]  

(25)

where \( C_E \) and \( K_D \) relate to the Poisson’s ratio, \( \nu \), modulus, \( E \), and diameters of the two impacting bodies via:

\[
C_E = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}
\]  

(26)

\[
K_D = \frac{D_1 D_2}{D_1 + D_2}
\]  

(27)

Design decisions are made based on these formulas. For the maximum stress to be low, soft, large-diameter impacting bodies are desirable. However, for a short tap with a large peak force that is rapidly removed, stiff materials are needed. Since plastic deformation of the part or impacting head is unacceptable, it is necessary to constrain the material properties first, so
that the maximum stress at the impact site is lower than the yield stresses of the colliding materials. For a maximum force, \( P \), of 250 N (56 lbs), Equation (24) is rewritten as:

\[
\sigma_{\text{max}} = 0.918 \sqrt{\frac{250}{K_D^2 C_E^2}} \leq \sigma_y
\]

(28)

The material properties for several relevant materials are tabulated in Table 4 [35]:

**Table 4: Relevant Material Properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus, ( E ) (GPa)</th>
<th>Poisson’s Ratio, ( \nu )</th>
<th>Compressive Yield Strength (MPa), ( \sigma_y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>69</td>
<td>0.33</td>
<td>200</td>
</tr>
<tr>
<td>Uranium</td>
<td>190</td>
<td>0.22</td>
<td>200</td>
</tr>
<tr>
<td>Steel</td>
<td>200</td>
<td>0.29</td>
<td>1700</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>1.83 – 3.70</td>
<td>~0.3</td>
<td>20 – 123</td>
</tr>
<tr>
<td>Acrylic</td>
<td>.95 - 4.5</td>
<td>0.37</td>
<td>36.5 – 124</td>
</tr>
</tbody>
</table>

The diameter of the hemispherical part is taken as 140 mm (5.51”), and the radius of curvature of the impacting head is chosen as 25 mm (1"). This large radius will allow the contact forces to be spread out over a larger area. A soft impacting head is needed because the low modulus allows the head to compress more during the impact. This expands the area over which the force is applied, thus reducing the stress. However, the soft head also lengthens the impact stroke.

The impact stroke, \( y \), is a function of applied force, \( P \), as described in Equation (25). This relation is plotted Figure 65 for an impact between and aluminum hemisphere with 140 mm diameter and a polyethylene impacting head with radius of curvature of 25 mm and modulus of 2 GPa.
Figure 65: Variation of Impact Stroke with Applied Force

Figure 65 shows that an impact stroke of about 75 µm (0.003”) will develop a peak force of 250 N (56 lbs). At the moment the impact starts, the approach of the center-points of the two impacting bodies, y, is zero. As the impact progresses the force that the actuator is exerting on the part increases. The initial kinetic energy of the moving element that is required to generate an impact stroke of 75 µm and peak force of 250 N can be found via:

\[ E_0 = \int_{y=0}^{y=75} P(y) \, dy \]  \hspace{1cm} (29)

Equation (29) represents the area under the curve in Figure 65. The integral is solved below:

\[ E_0 = \int_{y_0}^{y_f} \left( \frac{y}{1.040} \right)^{\frac{3}{2}} \left( \frac{K_D}{C_E^2} \right)^{\frac{1}{2}} \, dy \Rightarrow 2 \left( \frac{K_D}{C_E^2} \right)^{\frac{1}{2}} \left. y^{\frac{5}{2}} \right|_{y_0}^{y_f} \]  \hspace{1cm} (30)

Solving with \( y_0 \) equal to zero and substituting in Equation (25) for \( y \), Equation (30) can be solved for the initial kinetic energy required to produce a peak impact force, \( P \).
\[ E_0 = \frac{2 \cdot 1.040^2}{5} \frac{C_E^2}{K_D^{\frac{1}{3}}} P^3 \]  

Equation (31) is plotted in Figure 66.

\[ \text{Figure 66: Initial Kinetic Energy, } E_0, \text{ Required to Produce Peak Force, } P \]

An initial kinetic energy of 0.00763 Nm is required to produce a peak force of 250 N (56 lbs). Since kinetic energy is:

\[ KE = \frac{1}{2} mv^2 \]  

A 95 g (0.11 lbs) impacting element would need to have an impact velocity of 0.401 m/s (1.31 ft/s) to produce a peak force 250 N. The initial momentum would be:

\[ M = mv \]  

From Equation (33), the required element momentum is 0.0381 Ns. This is the momentum that has to be imparted by the actuator onto the moving mass to produce an impact with a peak force of 250 N.
5.7.2 Simulated Impact Force Profiles

The force and stress profiles during a collision between a 95 g translating actuator element and a stationary hemisphere is simulated using a discrete time model, which can be found in Appendix A. The applied force is calculated from Equation (25) and the maximum stress over the impacting area at each time is calculated from Equation (24). The parameters in Table 5 were used for the simulation plotted in Figure 67.

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter (cm)</th>
<th>Modulus (GPa)</th>
<th>Poisson’s Ratio</th>
<th>Yield Stress (MPa)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part</td>
<td>Aluminum</td>
<td>23.2</td>
<td>69</td>
<td>.33</td>
<td>200</td>
</tr>
<tr>
<td>Impacter</td>
<td>Acrylic</td>
<td>10.4</td>
<td>4</td>
<td>.37</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5: Impact Simulation Parameters [35]

These simulations show how the impact force and stress behave during impacts of different magnitudes. A tap that generates a peak force of 275 N will produce a peak stress over the area of the impact of 95 MPa. This value is below the yield stress for both materials involved in the collision. An understanding of the peak stress allows a designer to choose impacting head with a shape and modulus that will not plastically deform the part during the
collision. If the modulus of either material is increased the force and stress profiles become narrower and have a higher peak value.

5.7.3 Observed Impact Force Profiles

The force profile during a tap was measured using a piezoelectric load cell in the test setup shown in Figure 71. A curved piece of Aluminum was glued to the load cell to simulate the surface of a hemispherical part. Also, the velocity at impact was measured by integrating the output of an accelerometer attached to the translating element of the VCM.

![Test Setup Used for Measuring Impact Force Profiles](image)

Figure 68: Test Setup Used for Measuring Impact Force Profiles

Measured force profiles are shown for two different impacts in Figure 69. The simulation is run at the measured impact velocity and plotted as a dotted line in Figure 69. This comparison shows that the measured force profiles are narrower and have a lower peak than the simulations run for the same impact velocity. In effect, the measured impacts contain less energy than the ideal impacts from the simulation. This suggests that there is some energy loss during the collision. Typically, elastic collisions have an energetic coefficient of restitution that is less than 1, because of energy loss due to heating, friction, and plastic deformation [40]. Also, measuring velocity by integrating acceleration may result in some error.
Regardless, the experimental results show that the observed force profile is qualitatively similar to the simulated force profile. This suggests that the maximum stress experienced by the impacting bodies, which cannot be measured directly, will behave qualitatively similar to the simulation. This serves as evidence that repeated impacts will not plastically deform the part or actuator head. Measurements of impact locations taken with a Taylor Hobson Talysurf Profilometer verify that the form of the part is not permanently altered during actuation.

5.8 Part Alignment Testing

5.8.1 Behavior Simulation

It is desirable to understand the motion of a part retarded by friction both during and after an impact. This behavior is simulated based on the Hertzian deflection analysis in Section 5.7 and a friction force that varies according to Equation (20) in Section 5.3.2.
Figure 70 shows the response of a hemispherical part to an applied impact. It also shows how the applied impact and retarding friction forces vary through an ideal actuation step. The translating mass of the hypothetical alignment actuator is given an initial momentum of 0.03 Ns. The static friction coefficient is taken as 0.25 and the dynamic friction coefficient as 0.19.

Figure 70: Simulated Part Position Due to During Applied Impact

Figure 70 shows that the part begins to accelerate at 0.15 ms, immediately after the impact force exceeds the friction force. The force plot shows that the motion of the part reduces the friction force. The area between the friction force and impact force lines is equal to the momentum transferred to the part. Although this model provides a demonstration of the physical mechanisms at work during a tap-slip process, it cannot be used to accurately
predict the displacement of a part. First, the friction force will vary depending on the interface conditions. Also, the impact force is idealized and does not quantitatively match experimental results. These errors make it necessary to calibrate the realignment actuator experimentally.

5.8.2 Initial Calibration of the Realignment Actuator

The displacement of the hemispherical part caused by an impulse applied by the realignment actuator was measured repeatedly. The part was held on the vacuum chuck by a 10 in Hg (0.34 bar) vacuum pressure which generated a normal force of about 520 N (117 lbs). The test setup in Figure 71 was used to determine the translational motion of the hemispherical part after an applied impulse. A Federal gage is used to measure displacement, and the realignment actuator is supplied with a controlled voltage input multiplied by various gains, as shown in Figure 59.

![Test Setup Used for Initial Calibration of Realignment Actuator](image)

**Figure 71**: Test Setup Used for Initial Calibration of Realignment Actuator
On each impulse magnitude setting, the part is tapped by the actuator 10 times from 10 different randomly generated directions, \( \theta \). The average and standard deviation of the displacement of the part due to these 10 impacts are plotted in Figure 72. The average translational displacement of the part increases as the magnitude of the applied impulse increases, as expected.

The “percent” field shows repeatability as a percentage of the total displacement caused by a given impulse, as calculated in Equation (35). Note that the lower-energy impacts have a larger relative repeatability error than harder impacts, where the standard deviation is only 20% of the average. For lighter impacts, the standard deviation of the displacement is as large as 60% of the average. This suggests that either the input impulse is not repeatable, or that the friction force varies with the orientation of the part, \( \theta \).

\[
\text{percent} = \frac{\text{stddev}}{\text{avg}} \times 100
\]  

(35)

\[ \begin{array}{cccc}
\text{Impulse Gain} & \text{Displacement (\text{\(\mu m\))}} \\
0.50 & 0.00 & 0.00 & 0.00 \\
0.60 & 5.00 & 5.00 & 5.00 \\
0.70 & 10.00 & 10.00 & 10.00 \\
0.80 & 15.00 & 15.00 & 15.00 \\
0.90 & 20.00 & 20.00 & 20.00 \\
1.00 & 25.00 & 25.00 & 25.00 \\
\end{array} \]

\[ \begin{array}{cccc}
\text{Displacement (\text{\(\mu m\))}} & \text{Percent Error} \\
0.00 & 0.00 & 0.00 \\
5.00 & 5.00 & 5.00 \\
10.00 & 10.00 & 10.00 \\
15.00 & 15.00 & 15.00 \\
20.00 & 20.00 & 20.00 \\
25.00 & 25.00 & 25.00 \\
\end{array} \]

\[ \begin{array}{cccc}
\text{Impulse Gain} & \text{Percent Error} \\
0.50 & 0.00 & 0.00 \\
0.60 & 5.00 & 5.00 \\
0.70 & 10.00 & 10.00 \\
0.80 & 15.00 & 15.00 \\
0.90 & 20.00 & 20.00 \\
1.00 & 25.00 & 25.00 \\
\end{array} \]

\[ \begin{array}{cccc}
\text{Impulse Gain} & \text{Percent Error} \\
0.50 & 0.00 & 0.00 \\
0.60 & 5.00 & 5.00 \\
0.70 & 10.00 & 10.00 \\
0.80 & 15.00 & 15.00 \\
0.90 & 20.00 & 20.00 \\
1.00 & 25.00 & 25.00 \\
\end{array} \]

\[ \begin{array}{cccc}
\text{Impulse Gain} & \text{Percent Error} \\
0.50 & 0.00 & 0.00 \\
0.60 & 5.00 & 5.00 \\
0.70 & 10.00 & 10.00 \\
0.80 & 15.00 & 15.00 \\
0.90 & 20.00 & 20.00 \\
1.00 & 25.00 & 25.00 \\
\end{array} \]

\[ \begin{array}{cccc}
\text{Impulse Gain} & \text{Percent Error} \\
0.50 & 0.00 & 0.00 \\
0.60 & 5.00 & 5.00 \\
0.70 & 10.00 & 10.00 \\
0.80 & 15.00 & 15.00 \\
0.90 & 20.00 & 20.00 \\
1.00 & 25.00 & 25.00 \\
\end{array} \]

\[ \begin{array}{cccc}
\text{Impulse Gain} & \text{Percent Error} \\
0.50 & 0.00 & 0.00 \\
0.60 & 5.00 & 5.00 \\
0.70 & 10.00 & 10.00 \\
0.80 & 15.00 & 15.00 \\
0.90 & 20.00 & 20.00 \\
1.00 & 25.00 & 25.00 \\
\end{array} \]

**Figure 72:** Displacement of Hemishell Part Due to Impacts from Random Angles

To test whether the friction force varies with the direction of translation, dictated by the angular orientation of the part on the spindle, \( \theta \), the test above was repeated at 90 degree angular intervals rather than random angles. The results, plotted in Figure 73, show that the
friction force is lower in the 0 and 180 degree direction than in the 90 and 270 degree direction. The mechanism for this direction dependent variation in friction force is not clear. Note that both of the contacting surfaces are diamond turned aluminum, and each data point plotted represents the average displacement caused by 10 repeated impacts.

![Graph showing displacement vs. impulse gain for different angles](image)

**Figure 73:** Displacement of Hemishell Part Due to Impacts Applied at 90 Degree Intervals

### 5.8.3 Variation in Friction during Velocity Reversal

It was also observed that when the direction of a tap was reversed (θ changed by 180 degrees), the first few taps following the reversal produced large displacements. Figure 74 shows that Tap 1, which was applied after the impact direction was reversed, produced a larger displacement than Tap 2 and so forth. When the direction was reversed 5 more times, the part followed the paths in Figure 75.
Figure 74: Displacement of Part Due to Successive Taps at Impulse Magnitude 0.5

Figure 75: Displacement of Part Due to Successive Taps at Impulse Magnitude 0.5

The reversal in actuation direction shows that there is hysteresis in the friction force. This hysteresis is obvious when the impulse magnitude is 0.6, and to a lesser extent 0.7, shown in Figure 76 and Figure 77, respectively.
Figure 76: Displacement of Part Due to Successive Taps at Impulse Magnitude 0.6

Figure 77: Displacement of Part Due to Successive Taps at Impulse Magnitude 0.7

Figure 78 shows that the hysteresis loop is hardly noticeable when the impulse magnitude is 1.0. The shrinking of the hysteresis loop as the displacement of each tap increases suggests that the effect is displacement dependent. When the impacts have lower energy, as in impulse magnitude of 0.5 and 0.6, the large displacements persist for the first several applied taps after reversal. When higher-energy impacts of 0.7 and 1.0 are used, the hysteretic effect is only noticeable for the very first tap, at most.
These results reinforce the theory presented by Canudas, Futami, and Park, et. al. in Section 5.3 [7, 8, 30]. The friction interface is described as having elastic bristles that deform when the contacting surfaces translate with respect to one another shown in Figure 79. This effectively allows some strain to build up in the interface. However, it is apparent that this strain does not relax quickly when the applied load is removed, and is thus maintained between taps. The retarding force appears to be smaller before some strain limit is reached. However, once this strain limit is met the retarding force becomes equal to the static friction force. The tests above suggest that the strain limit is met between 2 and 6 µm (80-240 µin) of displacement.

5.8.4 Implications of Hysteresis for Realignment

The existence of a region of low retarding force after velocity reversal affects the fidelity of an alignment impact. The displacement of a part can vary by as much as 10 times for a
given, low-energy impact, depending on the history of the motion of the sliding surface. During realignment, it is possible for one set of impacts to push the part past the desired position. The next iteration of alignment would then have to push the part in the opposite direction. However, since experiments have shown that the first few impacts from the opposite direction will result in abnormally large displacements, the part will likely overshoot again. Although this effect is small, it may result in 2-6 µm of positioning uncertainty and delay the convergence of the part center-point to the spindle centerline.

The temporary reduction of friction due to velocity reversal is also considered in the realignment procedure outlined in Section 5.9. When the realignment actuator is calibrated, the first few impacts from a given direction are ignored. This eliminates the outlying, large displacement steps from the average that is used in calibration. The calibration values are then used in an algorithm which calculates the number and magnitude of the impacts needed to move the part. This algorithm always attempts to find an impulse magnitude that will require more than 10 impacts to move the part center to the spindle centerline. Finally, the calibration factors update as a part is aligned, so if a part continually overshoots the desired final position, the calibration factors are adjusted based on the average displacement caused by each impact applied during the previous move. This will effectively eliminate the chance of the part perpetually overshooting its target.

5.9 Realignment Procedure

The procedure below describes the method for centering a part on a vacuum chuck. The steps described are specific to the Rank Pneumo ASG 2500 Diamond Turning Lathe at the NC State University Precision Engineering Center. This is a single-spindle machining center with a single tool/probe slide. The spindle position and velocity and the realignment actuator are controlled with a dSPACE controller. The dSPACE connections required to run the realignment system as well as the full procedure for implementing the system is detailed in Appendix D.
5.9.1 Spindle Control and the U.I.

It was necessary to design a controller to regulate the position and velocity of the Diamond Turning Machine (DTM) spindle. The spindle position and velocity are measured via the spindle encoder. The control system was a dSPACE platform and is based on the compiled Simulink model described in Appendix D. The position and velocity controllers use PID and PI feedback, respectively. ControlDesk is used to generate a user interface (UI), shown in Figure 80. The UI can be operated in velocity or position mode. The velocity or position can be controlled with the slider bars shown. The operator can also set the realignment actuator impulse magnitude and apply impacts from the ControlDesk UI.

![ControlDesk User Interface](image)

**Figure 80:** ControlDesk User Interface

5.9.2 Setup

The OC Chuck, Touch Probe, and Realignment Actuator, as well as an optional electronic gage, are set up on the DTM as shown in Figure 81. The procedure for properly referencing and aligning the particular components used for this experiment is listed below. Note that these steps do not need to be repeated each time a new part is aligned.
1) Center the OC chuck on the spindle.
2) Mount the touch probe to the x slide to the right of the OC chuck, as shown in Figure 81.
3) Touch the OC Chuck x and z fiducials with the touch probe and set the machine relative coordinates to $x = 0, z = 0$. Also reset the dSPACE x coordinate to zero.
4) Move the machine axes to $x = 1.5, z = 6$.
5) Secure the realignment actuator to the x slide so it is aligned with the spindle centerline in $x$.

### 5.9.3 Realignment Steps

The basic realignment procedure is listed below.

1) Place the part on the OC Chuck.
2) Calibrate the realignment actuator.
3) Measure the run-out to determine the run-out magnitude and the impact direction.
4) Determine the number of impacts, n, and impulse magnitude, G, needed for realignment.
5) Set the ‘Tap Impulse Magnitude’ on the UI to G and tap the part n times.
6) Repeat the runout measurement.
7) If the run-out magnitude is greater than 5 µm, repeat steps 3-6.

**Realignment Actuator Calibration**

A front view of the part, actuator, and probe setup is shown in Figure 82.

![Diagram of part, actuator, and touch probe setup](image)

**Figure 82:** Front View of Part, Actuator, and Touch Probe Setup

1) Place the part on the OC chuck with \( \theta = 90 \) deg. adjacent to the touch probe as shown in Figure 82 and set the vacuum pressure to 10 in. Hg.
2) Set the Impulse Magnitude gain, G, to 0.7 and tap the part 5 times.
3) Rotate so \( \theta = 0 \) deg. is adjacent to the touch probe and touch the part with the touch probe by moving the x slide in, then back out. Record the x value at trigger, R0.
4) Rotate to \( \theta = 90 \) deg., set G to 0.6, and tap the part 5 times.
5) Rotate to $\theta = 0$ deg. touch the part with the touch probe and record $R_1$.
6) Repeat steps 4 and 5 for $G = 0.7, 0.8, 0.9, \text{ and } 1.0$. Fill in Table 6.

**Table 6:** Actuator Calibration Table

<table>
<thead>
<tr>
<th>Gain</th>
<th>$R$ (mm)</th>
<th>$\delta$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>$R_0 =$</td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>$R_1 =$</td>
<td>$200*(R_1-R_0)$ =</td>
</tr>
<tr>
<td>0.70</td>
<td>$R_2 =$</td>
<td>$200*(R_2-R_1)$ =</td>
</tr>
<tr>
<td>0.80</td>
<td>$R_3 =$</td>
<td>$200*(R_3-R_2)$ =</td>
</tr>
<tr>
<td>0.90</td>
<td>$R_4 =$</td>
<td>$200*(R_4-R_3)$ =</td>
</tr>
<tr>
<td>1.00</td>
<td>$R_5 =$</td>
<td>$200*(R_5-R_4)$ =</td>
</tr>
</tbody>
</table>

**Run-out Measurement using Touch Probe**

1) Rotate the part to $\theta = 0$ deg.
2) Set capture time to $\sim150$ s and start data capture by clicking “Start” on the Control Desk.
3) Within 10-15 seconds of starting data capture, execute program runout.mm n times, where n is greater than 3. Each time the probe trigger light turns from red to green, rotate the spindle $360/n$ degrees using the ControlDesk UI. Use command (b) to execute part program (a) n times.
   a. runout.mm:
      units metric
      move 1.5 6 250
      move 4.5 6 20
      move 1.5 6 80
   b. run rstep runout.mm n
4) After the part program is finished, stop capturing data by clicking “Stop” on the UI.
5) Save the captured data as data1.mat in the appropriate folder.
6) In the MATLAB GUI shown in Figure 83, set the pull-down menu to “Touch Probe” and click “Calculate” to determine the run-out magnitude and direction as well as the number of impacts and impulse magnitude needed for realignment †.

![MATLAB GUI for Calculating Run-out](image)

**Figure 83:** MATLAB GUI for Calculating Run-out

**Run-out Measurement using Electronic Gage**

The run-out of the part can also be measured using an analog signal from an electronic gage set up as shown in Figure 81.

1) Rotate the spindle at 10 RPM (6 seconds per revolution).
2) Set capture time to 6 s and start data capture and clicking “Start” on the UI. With the sample rate at 1 kHz, the ControlDesk will record 6000 data points during the one rotation.
3) Save the captured data.
4) In the MATLAB GUI shown in Figure 83, set the pull-down menu to “Electronic Gage” and click “Calculate” to determine the run-out magnitude and direction as well as the number of impacts and impulse magnitude needed for realignment.

† The algorithm for calculating the number of impacts and impulse magnitude is shown in the next section.
Algorithm for Calculating Number of Impacts and Their Impulse Magnitude

The run-out measurement and data from the calibration table are used to determine the number of impacts and impulse magnitude needed to center the part. Note that since the measuring probe is aligned 90 degrees from the actuator, as shown in Figure 82, the part must be rotated to the calculated run-out direction minus 90 degrees before the actuation impacts are applied.

1) Divide run-out magnitude, Rmag, by 10.
2) From the calibration Table 6, select the largest δ value that is less than Rmag/10 and call it δG. Record the associated input gain, G.
3) Round Rmag/δG down to the next lowest integer, n. n and G are the number of impacts and impulse magnitude needed.
4) If more than 50 taps are prescribed, the algorithm will attempt to pick a higher gain and allow fewer than 10 impacts.

5.10 Results of Realignment Demonstration

The procedure above is used to center a part that has either been manually placed on the OC chuck or automatically transferred from the IC chuck to the OC chuck. Before an adaptive calibration scheme was implemented, trials showed that a poor initial calibration could prevent the part from converging to within 5 μm of the spindle centerline. For example, assume that the initial calibration predicted that the part would move 20 μm under a given impact energy. If the run-out was measured to be 500 μm at 0 deg., the non-adaptive algorithm would tell the operator to apply 25 impacts from 0 degrees. However, if the calibration value was bad and the part actually moved 40 μm with each impact, the part would overshoot the spindle center and end up at 500 μm at 180 deg. The algorithm would then determine that the user should apply the same impacts in the opposite direction, once again resulting in overshoot. In this case, where the calibration factor underestimates the
displacement of the part by a factor of 2, the part will never converge on the spindle centerline.

Multiple tests showed that a larger error in the initial calibration would cause the realignment to take more steps to converge. Although friction force does not change greatly while a part is on the chuck, the interface can change while one part is replaced with another, thus corrupting the calibration factor.

To overcome this impediment to convergence, an adaptive calibration scheme is used to update the calibration values in Table 6 after each move. In the example above, the computer would recognize that 25 impacts produced a 1000 µm total displacement and would then update the calibration value to 40 µm/impact. Then on the second step the part would converge to the spindle centerline. Once this adaptive calibration scheme was applied, a part could be manually placed on the OC chuck with run-out ~1 mm and realigned; in all of the tests done with the adaptive calibration scheme, the part never failed to converge. Since the adaptive calibration scheme needs to see the result of a tap at a given impulse magnitude to update the calibration value for that impulse, a poor set of initial calibration data can still result in realignment taking as many as 10 iterations.

Figure 84 shows the location of the part on the spindle after each iteration for several tests using the adaptive algorithm. All of the tests shown converge in less than 7 steps. It may be beneficial to reduce the number of available impulse magnitude gains so that there is only a “coarse adjustment impact” and a “fine adjustment impact.” Then the adaptive calibration scheme would only have to update calibration values for 2 impulse magnitudes, thus reducing the number of iteration steps required. Note that the radial scale is logarithmic.
**Figure 84:** Path of Part during Various Centering Operations
6 Summary and Future Work

6.1 Background and Objectives

Technology for automating the fabrication of two-sided parts on a dual-spindle diamond turning lathe can improve the manufacturing process in a number of ways. First, automated handling technology can enable two-sided parts such as lenses and hemisshells to be produced in a closed, controlled environment (i.e. inside a glovebox). Also, an automated process can improve repeatability, reduce human effort, and eliminate many of the human-induced error sources.

The process for creating two-sided parts involves transferring the part from a chuck used to hold the part while the first side is machined to another chuck used to hold the part while the second side is machined. Then the part must be centered on the second chuck to ensure that features on the two sides are properly aligned.

The first objective of this study is to automatically transfer a hemispherical part from one chuck to another. During the transfer, the axial separation must be at least 125 µm. Also, the variation in radial separation between the outer diameter of the hemispherical and the concave pot chuck must be less than 8 µm. This implies that the distance between the centerlines of the spindle and an ideal hemispherical part should be less than 4 µm.

The second objective of this study is to automatically center the hemispherical part on a flat-faced vacuum chuck. The centering method must be capable of correcting an initial run-out error as large as 2.5 mm to less than 5 µm. This capability can correct run-out errors from two sources: a part that is either manually placed on the OC chuck or a part that is transferred from the IC to OC chuck.
6.2 Transfer

An automatic part measurement and transfer procedure has been developed and demonstrated on the NC State University Precision Engineering Center’s Rank Pneumo ASG 2500 Diamond Turning Lathe. A touch probe was selected to locate points on the surface of a part and holding fixture because it can be triggered from almost any direction and can survive an over-travel of up to 6 mm. The touch probe is mounted to a machine axes with laser interferometer feedback which provides the measurement scale. When the touch probe head contacts the part it provides a trigger, which indicates that the location of the x and z slides should be recorded. Many of the probing errors, such as pre-travel, were calibrated using a precision sphere. As a result, points on a fiducial or part surface could be located with an uncertainty of 300 nm—the trigger repeatability of the Renishaw TP-6 touch probe used in the demonstration tests. Errors in the x and z slides were deemed to be negligible and ignored.

By touching a spherical part in three places, the radius and center point of the part were calculated. When using this three-point method, the touch probe repeatability error contributes to uncertainty in the measurement of the size and center-point location of a spherical part. The size of an ideal part can be determined with an uncertainty of 1.6 μm (63 μin.), and the center-point of the part location can be determined with a 1.4 μm (55 μin.) uncertainty. Measuring the size of the part ensures that it will fit into a receiving chuck. Measuring the location of the part and opposing chuck in the same coordinate system allows the coordinates of the transfer move to be calculated.

Both IC to OC and OC to IC part transfers were demonstrated at the PEC. In the OC to IC transfer the maximum variation of the radial separation between a perfectly machined part and pot chuck can be controlled to within 3 μm (100 μin.). This is significantly less than the requirement of 8 μm (315 μin.) proposed in the Statement of Work. This means that the centerline of the hemispheric part can be positioned within ± 1.5 μm of the spindle centerline, when the requirement was ± 4 μm. Also, the axial position at transfer can be
controlled to within 5 μm (200 μin.)—the planned axial separation at vacuum transfer is 125 μm (0.005”).

6.3 Realignment

Automated realignment requires a two-step process: first the position of the part with respect to the spindle center must be measured then the part must be moved towards the spindle center. This process is then repeated until the measured run-out is less than 5 μm.

6.3.1 Run-out Measurement

Either a touch probe or an electronic gage can be also used to measure the run-out of a hemispherical part on the OD chuck. The touch probe method relies on the machine axes for a measurement scale, while a calibrated electronic gage is capable of measuring absolute displacements on its own. For the case of a run-out measurement with a touch probe, an algorithm has been presented for determining the number of touch points needed to ensure that a part with 25 μm (0.001”) form error is centered within 5 μm (200 μin.) of the spindle centerline. That algorithm shows that if 15 touch points are used, the center of the roughly machined hemispherical part can be determined with an uncertainty of 2.9 μm (114 μin.).

Run-out measurement tests verified that using more touch points tends to reduce the run-out measurement uncertainty of a part with form errors. For example, using 3 touch points results in a measurement uncertainty of 6.62 μm and 9 points results in uncertainty of 1.34 μm. When an electronic gage is used, 6000 points are sampled through 1 revolution of the part and the resulting uncertainty is 0.04 μm. These values for measurement uncertainty represent the limit of the precision of realignment.

6.3.2 Realignment Actuator Design

An actuator has been designed to center the part by overcoming the force holding the part on the vacuum chuck—friction. The friction interface was studied and stick-slip behavior was observed. Modeling showed that the best possible actuator resolution would result from an
applied impact, which causes a large actuation force over a very short period of time. The actuator uses a voice coil motor (VCM) to accelerate a mass to the velocity needed to produce a desired force profile during impact. The approximately uniform force output of the VCM with stroke make it possible for a simple waveform to be used to approximately counter friction and gravity after the translating mass is accelerated. This allows the actuator to hold the velocity of the translating mass constant through several millimeters of stroke. As the part moves during actuation, the translating mass will strike the part at a different spot in its stroke; however, since the velocity of the translating mass can be held constant, the impulse energy applied by the impacts remain repeatable.

The design of the impacting head of the actuator was based on modeling of the Hertzian deflection between the part surface and actuator head. Theoretical force and surface stress profiles are calculated during a simulated collision. The behavior of these profiles depends on the material properties and geometry of the impacting bodies during a perfectly elastic collision. Simulation predicts that a collision between a 95 g mass with a 5 cm radius plastic impacting head moving at 0.2 m/s and an aluminum part with radius of 12 cm will result in a peak actuation force of 170 N and peak stress of 80 MPa. Experiments show that the actual impacts are less energetic than the simulated impacts, which is expected because there is no collision is truly elastic. However, simulations demonstrate that even in the perfectly elastic case the stress on the colliding bodies, which cannot be measured directly, will be less than the yield stress of the materials.

6.3.3 Results of Realignment Tests

Realignment tests showed that the friction force exhibits hysteretic behavior. As the part is actuated in one direction the displacement caused by each impact is fairly repeatable. However, when the part actuation direction is reversed, the first few alignment impacts produce part displacement that is substantially larger than average. Also, changes in the conditions at the friction interface result in disparity of displacement caused by a given impact. As a result, realignment actuator must be calibrated for a number of impulse magnitudes.
A part centering procedure was developed. First the actuator is calibrated—the displacements caused by impacts of several impulse magnitudes are recorded. Then the run-out is measured by touching several points on the hemispherical surface of the part and calculating a best fit circle. The center of this circle represents the part location, and the difference between the part location and the spindle centerline is the run-out. An algorithm is then run to calculate the number of impacts required at a given impulse magnitude to center the part. Initially, previously recorded calibration values are used in this algorithm. However, since poor initial calibration values can result in non-convergence, it is necessary to update the calibration values based on the previous actuation steps. This adaptive calibration scheme succeeded in aligning a part to within 5 µm of the spindle centerline in less than 7 steps every time tested. In each of these tests, the part was manually placed on the OC Chuck and an initial run-out of 1-2 mm was corrected.

6.4 Future Work

In the automatic transfer procedure, more work could be done to determine the measurement uncertainty for a part with form errors. Currently, the size of the part is determined based on three touch points. While this method is accurate for a diamond-turned hemisphere with very small form errors, it will produce larger measurement errors if used for roughly machined parts.

The realignment system can be improved substantially with additional work. If a long-range analog gage can be used to measure the position of the part at all times during alignment, the number of steps and time required for a centering operation could potentially be reduced from 5-10 minutes to less than 1 minute. With an analog gage constantly measuring the displacement of the part, the impacts can be repeated until the analog gage returns the desired position measurement. This would essentially close the loop on the positioning process, and eliminate the need to calibrate the realignment actuator and calculate the number and impulse magnitude required for centering. Since an analog gage can only measure displacement in
one direction, errors may still result if the part does not move exactly along the measurement direction of the gage during actuation. However, during realignment tests these errors were typically observed to be second order. Convergence will still take multiple iteration steps.

Additional work could also be done to make the realignment procedure and user interface more robust to changes in the friction interface, vacuum pressure, part size and shape, as well as potential operator error. Also, in the future, the polyethylene head of the tapping actuator should not be sanded to its spherical shape. Instead, a plastic ball will be sectioned to provide a spherical surface. This will prevent the tapping head from becoming impregnated with carbide particles from the sandpaper and reduce the visible scuffing of the surface finish that has been observed. The improvements described will likely make this automated centering system fast and robust enough to be viable in the industrial setting.
REFERENCES


APPENDICES
Appendix A.  Touch Probe Signal Conditioner Block Diagram

Appendix B.  Hertzian Impact Model

% Written by Stephen Furst
% Written February, 2008
% HertzianCollisionFixed.m
% This program is designed to simulate the motion of a part retarded by % friction and a translating plunger.  Both the part and plunger have a % known diameter and material properties.  Equations for an elastic co- % lllision are based on Hertzian deflection and a Stribeck friction-based % model is used to simulate friction force.

clear all
close all

%-----------------
%Constant Parameters
%-----------------

m_p = .095;  % Mass of translating plunger, kg
m_s = .577;  % Mass of shell, kg
g = 9.81;    % Acceleration due to gravity, m/s^2
D1 = 2*.116; % Diameter of shell, m
D2 = 2*.052; % Diameter of tapper head, m
K_d = D1*D2/(D1+D2);
E1 = 6.9e10; % Modulus of aluminum shell, Pa
nu1 = 0.33; % Poisson's ratio of aluminum
E2 = 4e9;   % Modulus of polyethylene tapper head, Pa
nu2 = 0.37; % Poisson's ratio of polyethylene
C_e = (1-nu1^2)/E1+(1-nu2^2)/E2;
A = .06;    % Diff. btw static and dynamic friction coef.
% Static friction coeff.
B = .25;

% Decay rate of Strieber friction curve
b = 730000;

% Normal force due to vacuum, N
N = 520*(1000/10);

% Static friction force, N
F_s = (A+B)*N;

% Total simulation time, s
Endtime = .0006;

% Time interval, s
Intervals = Endtime/timestep;

% Initial Conditions
Gain = .8;
t(1) = 0;
X1(1) = 0;  % Plunger position
X2(1) = 0;  % Hemishell position
X3(1) = .223;  % Plunger impact velocity, m/s
X4(1) = 0;  % Hemishell velocity, m/s
X4dot(1) = 0;  % Force on hemishell, N
count = 1;

for i = 2:Intervals+1
    t(i)=t(i-1)+timestep;
    K(i) = (1/(1.040^1.5))*(K_d/(C_e^2))^0.5*(X1(i-1)-X2(i-1))^0.5;  % Non-linear stiffness between colliding bodies
    F_k(i) = K(i)*(X1(i-1)-X2(i-1));  % Force btw colliding bodies, N
    a(i) = .721*(F_k(i)*K_d*C_e)^0.3333;  % Impact area, m^2
    Sigma_max(i) = .918*(F_k(i)/(K_d^2*C_e^2))^0.3333;  % Max stress, Pa
    X1dot(i) = X3(i-1);
    X2dot(i) = X4(i-1);
    X3dot(i) = F_k(i)/m_p;
    if F_k(i) <= F_s  &&  X4(i-1) == 0  % Pre-sliding 'stick' phase
        F_f(i) = K(i)*(X1(i-1)-X2(i-1));
    elseif F_k(i) > F_s  % Sliding phase
        F_f(i) = N*(A/exp(b*X4(i-1))+B);
        count = 2;
    else  % Sliding phase
        F_f(i) = N*(A/exp(b*X4(i-1))+B);
    end
    if F_k(i) < 0  % Separation
        F_k(i) = 0;
        Sigma_max(i) = 0;
    end
    if X4(i-1) <= 0  &&  count == 2  % Separation
        F_f(i) = F_s;
    end
    X4dot(i) = F_k(i)/m_s - F_f(i)/m_s;  % Hemishell acceleration, m/s^2
\[ X1(i) = X1(i-1) + \text{timestep} \times X1\dot(i); \]
\[ X2(i) = X2(i-1) + \text{timestep} \times X2\dot(i); \]
\[ X3(i) = X3(i-1) + \text{timestep} \times X3\dot(i); \]
\[ X4(i) = X4(i-1) + \text{timestep} \times X4\dot(i); \]
\[
\text{if } X4(i) < 0 \\
\quad X3(i) = X3(i-1); \\
\quad X4(i) = 0; \\
\quad X1(i) = X1(i-1) + \text{timestep} \times X3(i); \\
\quad X2(i) = X2(i-1); 
\]
\[ y(i) = X1(i) - X2(i); \]
\[ \text{if } X4(i) < 0 \\
\quad X3(i) = X3(i-1); \\
\quad X4(i) = 0; \\
\quad X1(i) = X1(i-1) + \text{timestep} \times X3(i); \\
\quad X2(i) = X2(i-1); 
\]
\[ \text{Gain}; \]
\[ \text{ImpactVel} = X3(1); \]
\[ \text{PeakForce} = \max(F_k); \]
\[ \text{Displacement} = \max(X2) \times 1e6; \]

**Appendix C. Stick-Slip Friction Model**

% Written by Stephen Furst
% Written on 3-23-08
% stickslip.m
% This Program represents a model of the stick-slip behavior of a
% friction interface. A part, whose position is X2, is forced to
% move by a rigid body, X1, that is moving at a constant velocity,
% X1dot. The junction between X1 and X2 is modeled as compliant
% with damping.

clear all
close all

% Constants
ro=2700; % Density of block (kg/m^3)
r_o=.07220/2; % Outer radius (m)
r_i=.05504/2; % Inner radius (m)
V=3.14159*((.07564/2)^2)*.0248; % Volume of block (m^3)
A_I=3.14159*(r_o^2-r_i^2); % Interface area (m^2)
p=420*133.322; % Vacuum pressure (N/m^2)
A_p=3.14159*r_i^2; % Vacuum area (m^2)
m_h=.283; % Mass of hammer head (kg)
g=9.81; % Gravitational constant (m/s^2)
m=ro*V; % Mass of block (kg)
F_p=A_p*p+m*g; % Normal force due to vacuum and gravity (N)
Endtime=.003; % Simulation end time, (s)
deltat1=.0000004; % Time step
Friction Characteristics

\[ f_s = 0.25; \quad \text{Static friction Coef} \]

\[ f_d = 0.18; \quad \text{Dynamic friction coef} \]

\[ k = 1.25 \times 10^8; \quad \text{Interface stiffness (N/m)} \]

Dynamic friction, exponential function coefs

\[ A = f_s - f_d; \]
\[ b = 80; \]
\[ B = f_d; \]

Initial Conditions

\[ i = 1; \]
\[ \text{deltat}(1) = \text{deltat}1; \]
\[ X1(1) = 0; \]
\[ X1dot(1) = 0.0002; \quad \text{Constant Velocity Pusher} \]
\[ X2(1) = 0; X2dot(1) = 0; X2ddot(1) = 0; F_k(1) = 0; f(1) = 0; F_s(1) = 0; t(1) = 0; \]
\[ \text{Place}(1) = 0; \]

\[ c = 0000; \quad \text{Damping coefficient} \]

while \( t(i) < \text{Endtime} \)

\[ i = i + 1; \]
\[ t(i) = i \times \text{deltat}(i-1); \]
\[ X1dot(i) = X1dot(i-1); \]
\[ X1(i) = X1(i-1) + X1dot(i) \times \text{deltat}(i-1); \]
\[ F_d(i) = c \times (X1dot(i-1) - X2dot(i-1)); \quad \text{Damping} \]
\[ F_k(i) = k \times (X1(i-1) - X2(i-1)); \quad \text{Spring} \]

if \( \text{abs}(F_k(i) - f_s \times F_p) < 0.1 \)

\[ \text{deltat}(i) = \text{deltat}1; \]

else

\[ \text{deltat}(i) = \text{deltat}1; \]

end

if \( F_k(i) \leq f_s \times F_p \) \&\& \( \text{X2dot}(i-1) \leq 0 \) \quad \text{Elastic, ple-slide}

\[ F_f(i) = F_k(i); \]
\[ \text{Place}(i) = 100; \]

end

if \( F_k(i) > f_s \times F_p \) \quad \text{Sliding}

\[ F_f(i) = F_p \times \left( A/\exp(b \times \text{X2dot}(i-1)) + B \right); \]
\[ \text{Place}(i) = 200; \]

end

if \( F_k(i) \leq f_s \times F_p \) \&\& \( \text{X2dot}(i-1) > 0 \) \quad \text{Sliding}

\[ F_f(i) = F_p \times \left( A/\exp(b \times \text{X2dot}(i-1)) + B \right); \]
\[ \text{Place}(i) = 300; \]

end
Appendix D. Realignment System (dSPACE)

Implementing the dSPACE Spindle Controller on ASG Machine

1) Plug in the needed connections outlined in the figure above.
2) Open MATLAB and change the current working directory to C:\Documents and Settings\Graduate Student\Stephen.
3) Click the Simulink icon and open asg_spindle_control.mdl from the directory above.
4) In the Simulink block diagram window, click “Build All.”
5) Open dSPACE ControlDesk
6) Click File, Open Variable File, and open asg_spindle_control.sdf from the same directory as above.
7) Click File, Open and open realignmentinterface.lay.
8) Accept the previously saved connections when prompted.
9) In the ControlDesk window, click “Animation Mode” to run the interface.
The asg_spindle_control.mdl Simulink model is shown below.
ASG Spindle Position PID Controller

0_360 Deg Filter: Converts all angles to between 0 and 360 degrees.
Integrator Reset: Turns off integral control while the error is large to avoid overshoot.
Accumulator Resettable: Integrates position error.
Gains: \( P = -0.0005, I = -0.0000005, D = -0.001 \).
**ASG Spindle Velocity PI Controller**

Integrator Reset: Turns off integral control while the error is large to avoid overshoot.
Accumulator Resettable: Integrates position error.
Gains: $P = -0.002, I = -0.000005$. 
**Tapping Actuator Control**

Acceleration Phase: Generates the waveform that accelerates the actuators moving mass.

Hold Phase: Generates the waveform that counters friction and gravity.

Impulse Magnitude: Scales the input wave.

Tap On/Off: Switches the tapper on and off.

Counter: Counts the number of taps applied since the Tap On/Off switch is closed.

Reset Subsystem and Counter Reset Switch: Reset the tap counter.
Appendix E. Run-out Calculation and Move Algorithm

function varargout = guifile(varargin)
% Written by Stephen Furst
% Written on September 2008
% GUIFILE M-file for guifile.fig
% This file runs the graphical user interface for calculating run-out and
% determining the number and direction of the alignment move. It contains
% the touch point filter, which saves the touch probe trigger points. It
% also contains the algorithm for determining number and direction of the
% realignment taps based on a constantly updating calibration table.

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name', mfilename, ...
    'gui_Singleton', gui_Singleton, ...
    'gui_OpeningFcn', @guifile_OpeningFcn, ...
    'gui_OutputFcn', @guifile_OutputFcn, ...
    'gui_LayoutFcn', [], ...
    'gui_Callback', []);
if nargin & isstr(varargin{1})
gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before guiFILE is made visible.
function guifile_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to guifile (see VARARGIN)

% Choose default command line output for guifile
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% This sets up the initial plot - only do when we are invisible
% so window can get raised using guifile.
if strcmp(get(hObject, 'Visible'), 'off')
    plot(rand(5));
end
% --- Outputs from this function are returned to the command line.
function varargout = guifile_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

% --------------------------------------------------------------------
function FileMenu_Callback(hObject, eventdata, handles)
% hObject    handle to FileMenu (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% --------------------------------------------------------------------
function OpenMenuItem_Callback(hObject, eventdata, handles)
% hObject    handle to OpenMenuItem (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% file = uigetfile('*.fig');
if ~isequal(file, 0)
  open(file);
end

% --------------------------------------------------------------------
function PrintMenuItem_Callback(hObject, eventdata, handles)
% hObject    handle to PrintMenuItem (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
printdlg(handles.figure1)

% --------------------------------------------------------------------
function CloseMenuItem_Callback(hObject, eventdata, handles)
% hObject    handle to CloseMenuItem (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
selection = questdlg('[Close ' get(handles.figure1,'Name') ']',...
    ['Close ' get(handles.figure1,'Name') '...'],...
    'Yes','No','Yes');
if strcmp(selection,'No')
    return;
end

delete(handles.figure1)

% --- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton2 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Filter Trigger Points and Calculate Runout
load 'data1.mat'  % Loads file containing past alignment steps and calibration table
Method = dlmread('Method.dat');  % Touch Probe of Electronic Gage
A = zeros(length(data1.Y(1).Data),4);
A(:,1) = data1.Y(2).Data';    %Theta
A(:,2) = data1.Y(4).Data';    %X
A(:,3) = data1.Y(3).Data';    %Probe
A(:,4) = data1.Y(1).Data';    %Electronic Gage

if Method == 1  % Touch probe used to measure run-out
    j=1;
    for i = 50:length(A)-4
        if (A(i,3)<=3 && A(i-1,3)>3 && A(i-40,3) >4 && A(i+1,3)<3 && A(i+2,3)<3 && A(i+3,3)<3 && A(i+20,3)<1)
            d(j,1)=A(i,2);    % X axis position
            q(j,1)=A(i,1);    % Spindle angle, theta
            n(j,1)=i;
            j=j+1;
            i=i+10;
        end
    end

    if j < 4
        runout_out = 0;
        tapdir_out = 0;
        error('Not enough trigger points to calculate circle');
    end

    for i = 1:j-1
        %Convert from polar to cartesian coords
        r(i) = abs(d(i)-79.3925);
        theta(i) = q(i);
        x_r(i) = r(i)*cos(pi*theta(i)/180);
        y_r(i) = r(i)*sin(pi*theta(i)/180);
    end
    format long
    x_r;
    y_r;
elseif Method == 2;  % Federal gage used to measure run-out
    theta = A(:,1);
    r = A(:,4).*2238+76;
    for k=1:length(r)
        x_r(k) = r(k)*cos(pi*theta(k)/180);
        y_r(k) = r(k)*sin(pi*theta(k)/180);
        x_r(k) = x_r';
        y_r(k) = y_r';
end
j = length(r);
end

[xc, yc, R, rres] = circlefit2(x_r, y_r);  % Call circlefit function
num = j - 1;
runout = sqrt(xc^2 + yc^2);  % Run-out magnitude

if Method == 1  % Determine spindle pos. for realignment tap
    if xc < 0
        tapdir = atan(yc/xc)*180/pi + 90;
    elseif xc >= 0
        tapdir = atan(yc/xc)*180/pi + 270;
    end
    if tapdir > 360
        tapdir = tapdir - 360;
    end
else  % Determine spindle pos. for realignment tap
    if xc < 0
        tapdir = atan(yc/xc)*180/pi;
    elseif xc > 0
        tapdir = atan(yc/xc)*180/pi + 180;
    end
    if tapdir > 360
        tapdir = tapdir - 360;
    elseif tapdir < 0
        tapdir = tapdir + 360;
    end
end
runout_out = runout;  % Run-out magnitude
tapdir_out = tapdir;  % Direction to tap

%-------------------------------------------------------
% Read and update calibration values and calculate number of taps
% and impulse magnitude needed for realignment.
%-------------------------------------------------------
Cal = dlmread('Calibration.dat', '\t');
Cal2 = dlmread('Calibration2.dat', '\t');

G = [.6 .7 .8 .9 1];
if isempty(Cal) == true && isempty(Cal2) == true  % Initial calibration
    index = 1;
    % Calibration Table
    R0 = -.1295;
    R1 = -.1260;
    R2 = -.1074;
    R3 = -.0680;
    R4 = -.0010;
    R5 = .0960;
    Rcal = [R0; R1; R2; R3; R4; R5];
    D = runout/10;
    for i = 1:length(G)
delta(i) = .2*(Rcal(i+1)-Rcal(i)); % Displacement per tap, mm
if delta(i) < D
    delta_G = delta(i);
    j = i;
end
n = fix(runout/delta_G); % Integer number of taps
Gain = G(j); % Impulse magnitude
Run = [xc;yc;j;n;index];
Cal = [delta';Run];
elseif isempty(Cal) == true && isempty(Cal2) == false % Adaptive calibration
    index = 1;
    delta = Cal2;
    D = runout/10;
    for i = 1:length(G)
        if delta(i) < D
            delta_G = delta(i);
            j = i;
        end
    end
    n = fix(runout/delta_G);
    Gain = G(j);
    Run = [xc;yc;j;n;index];
    Cal = [delta; Run];
else
    [rows,cols] = size(Cal);
    index = Cal(rows,cols);
    delta_last(1) = Cal(1,index);
    delta_last(2) = Cal(2,index);
    delta_last(3) = Cal(3,index);
    delta_last(4) = Cal(4,index);
    delta_last(5) = Cal(5,index);
    xc_last = Cal(6,index);
    yc_last = Cal(7,index);
    j_last = Cal(8,index);
    n_last = Cal(9,index);
    Disp = sqrt((xc-xc_last)^2+(yc-yc_last)^2);
    delta_new = Disp/n_last;
    delta = delta_last;
    delta(j_last) = delta_new;
end
D = runout/10; % Try to use more than 10 taps
for i = 1:length(G)
    if delta(i) < D
        delta_G = delta(i);
        j = i;
    end
end
if exist('delta_G','var')==0
    delta_G = delta(1);
j=1
end
n = fix(runout/delta_G);
Gain = G(j);
if n > 50 && Gain < 1  % Don't use more than 50 taps
    Gain = G(j+1);
delta_G = delta(j+1);
n = fix(runout/delta_G);
j = j+1;
end

index = index+1;  % Alignment step
Cal(:,index) = [delta';xc;yc;j;n;index];
end

dlmwrite('Calibration.dat',Cal,'	');  %Save alignment move

set(handles.text1,'String',sprintf('%.5f',runout_out));
set(handles.text5,'String',sprintf('%.2f',tapdir_out));
set(handles.text7,'String',sprintf('%.0f',num));
set(handles.text10,'String',sprintf('%.0f',n));
set(handles.text11,'String',sprintf('%.1f',Gain));

thetaplot = linspace(0,2*pi,400);
xplot = R*sin(thetaplot);
yplot = R*cos(thetaplot);

plot(x_r,y_r,'*r')
hold on
plot(0,0,'+b')
plot(xc,yc,'om')
plot([0,R*cos((tapdir-90)*pi/180)],[0,R*sin((tapdir-90)*pi/180)],'-r')
plot([0,R*cos(tapdir*pi/180)],[0,R*sin(tapdir*pi/180)],'-g')
plot(xplot,yplot,'-m')
xlabel('X Pos. (mm)')
ylabel('Y Pos. (mm)')
axis equal
axis square
legend('touchpoints','origin','center','runout dir','tap dir',-1)
hold off

% --- Executes on button press in pushbutton3, "Go Back".
% Removes the most recent measurement and calibration update from
% Calibration.dat.
function pushbutton3_Callback(hObject, eventdata, handles)
    % hObject    handle to pushbutton3 (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    Cal = dlmread('Calibration.dat','	');
    [rows,cols] = size(Cal);
Cal(:,cols) = ';
dlmwrite('Calibration.dat',Cal,'
');

% --- Executes on button press in pushbutton4, "New".
% Clears all saved calibration data.
function pushbutton4_Callback(hObject, eventdata, handles)
    % hObject    handle to pushbutton4 (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    Cal = dlmread('Calibration.dat','
');
    [rows,cols] = size(Cal);
dlmwrite('Calibration2.dat',[Cal(1,cols);Cal(2,cols);Cal(3,cols);Cal(4,cols);Cal(5,cols)],'
');
    Cal = ';
dlmwrite('Calibration.dat',Cal,'
');

% --- Executes during object creation, after setting all properties.
function popupmenu2_CreateFcn(hObject, eventdata, handles)
    % hObject    handle to popupmenu2 (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    empty - handles not created until after all CreateFcns called
    if ispc
        set(hObject,'BackgroundColor','white');
    else
        set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
    end

% --- Executes on selection change in popupmenu2, measurement method.
function popupmenu2_Callback(hObject, eventdata, handles)
    % hObject    handle to popupmenu2 (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    Method = get(hObject,'Value');
dlmwrite('Method.dat',Method);

% --- Executes on button press in pushbutton5, "Clear All".
function pushbutton5_Callback(hObject, eventdata, handles)
    % hObject    handle to pushbutton5 (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    dlmwrite('Calibration.dat','','',
);
    dlmwrite('Calibration2.dat','','',
);
Appendix F. Run-out Measurement Uncertainty

% Written by Ken Garrard
% cp.m
% This program generates an ideal circle. It then positions some number of
% touch points around the circle, and adds a random error to each of those
% touch points. This represents a "real" part. This program then uses the
% circlefit function to repeatedly calculate the best fit circle of the
% touch points. The standard deviation of the run-out measurements is
% plotted vs the number of touch points used to measure the part.

% parameters
shell_radius = 70;
errMag = 1e-3;

% range of data points
Ns = 100;
Ne = 3;

% allocate space for results
x0 = zeros(Ns,1); % center of fit circle, x
y0 = x0; % y
R = x0; % best fit radius
mxr_err = x0; % largest residual error
center_err = x0; % distance from origin to x0,y0
angle = x0; % angle to 'high' spot

% run for each number of data points
for k = Ne:Ns;
    % set plot and print flags
    if k == Ns || k==Ne || mod(k,10)==0, plt = true;
    else plt = false;
end

    % simulation of circle fit with random error in data points
    [x0(k),y0(k),R(k),mxr_err(k),center_err(k),angle(k)] ...
    = cpfit(k,errMag,shell_radius,plt,plt);
end

% display final result, plot center error vs number of data points
figure;
plot(Ne:Ns,center_err(Ne:Ns)*1000,'Linewidth',2);
set(gca,'FontName','Arial','FontWeight','Bold','FontSize',14);
set(gca,'XDir','Reverse');
grid on;
ylabel('runout (\mu m)');
xlabel('number of data points');
title(sprintf('Simulated runout error, errMag = %.2f \mu m',errMag*1000));
function [x0,y0,R,mxr_err,center_err,angle] = cpfit(N,errMag,err_std_dev,Rad,plt,dspl)

if nargin < 1, N = 6; end
if nargin < 2, errMag = 1; end
if nargin < 3, Rad = 70; end
if nargin < 4, plt = true; end
if nargin < 5, dspl = true; end

% generate polar data points for circle at origin
th = linspace(0,2*pi*(1-1/N),N);
rr = ones(size(th))*Rad;

% uniform random errors in radius
% rad_err = (rand(size(rr)) - 0.5)*errMag;

% normally distributed random errors in radius
rad_err = (randn(size(rr)))*err_std_dev;

% add errors and convert to Cartesian
[xs,ys] = pol2cart(th,rr+rad_err);

% fit a circle to the data points
[x0,y0,R,rres] = circlefit(xs,ys);

% find maximum error, distance and angle to best fit center
[mxr_err,ix] = max(abs(rres));
mxr_err = mxr_err * sign(rres(ix));
center_err = hypot(x0,y0);
angle = atan2(y0,x0);

% positive angles, 0 .. 2pi
if angle < 0, angle = 2*pi + angle; end

% generate points on the fit circle
[x,y] = pol2cart(linspace(0,2*pi,1000),R);
x = x + x0;
y = y + y0;

% print results
tstr1 = sprintf(['N = %d, ErrMag = %.2f um, Radius = %.2f
'], N,errMag*1000,Rad);
   ['Fit Radius = %.2f, Center = %+.4f,%+.4f
'], N,errMag*1000,Rad,x0,y0);
tstr2 = sprintf('...
    'Max Residual = %.2e, Center Error = %.2f um at %4.2f deg', ...
mxr_err,center_err*1000,angle*180/pi);

if dspl, display([tstr1 tstr2]); end

% plot results
if plt
    figure;
    set(gcf,'Position',[90 300 1300 500]);
    subplot(1,2,1);
    set(gca,'FontName','Arial','FontWeight','Bold','FontSize',14);
    xlim([-(-mxr_err+Rad) (mxr_err+Rad)]* 1.1);
    ylim(xlim);
    xlabel('radius');
    ylabel('radius');
    title(tstr1(1:end-1));
    hold on; axis square; grid on;

    % plot data points and best fit circle
    plot(xs,ys,'ro',[x x(1)],[y y(1)],'b-','LineWidth',2);

    % add center data points to plot
    plot(0,0,'ks','MarkerSize',10,'LineWidth',2);
    plot(x0,y0,'mx','MarkerSize',14,'LineWidth',2);

    % add line from fit center to edge of fit circle at 'high spot' angle
    plot([0 R*cos(angle)]+x0,[0 R*sin(angle)]+y0,'m:','LineWidth',4);

    % plot data points in Cartesian coordinates
    subplot(1,2,2);
    set(gca,'FontName','Arial','FontWeight','Bold','FontSize',14);
    xlim([0 360]);
    ylim([-errMag errMag]*1000/2);
    xlabel('angle');
    ylabel('radial deviation (\mum)');
    title(tstr2);
    hold on; grid on;

    % plot data
    plot(th*180/pi,rad_err*1000,'ro',th*180/pi,rad_err*1000,'b-','LineWidth',2);

    % add vertical line at 'high' spot
    plot([angle angle]*180/pi,ylim,'m:','LineWidth',4);
end

**Circle Fit Function**

Written by Ken Garrard
% Fit a circle to a set of xy data points
%    [xc,yc,R,rres] = circlefit(x,y);
% Input
%    x,y   Cartesian data, n x 2 matrix or two n x 1 column vectors
% Output
%    xc    x center coordinate
%    yc    y center coordinate
%    R     radius of curvature
%    rres  residual radius vector, R minus data
%
% Fits the equation of a circle in Cartesian coordinates to a set of xy
data points by solving the overdetermined system of normal equations,
i.e.,  x^2 + y^2 + a*x + b*y + c = 0
% The least squares circle has radius R = sqrt((a^2+b^2)/4-c) and
% center coordinates (x,y) = (-a/2,-b/2)

function [xc,yc,R,rres] = circlefit(x,y)

error(nargchk(1,2,nargin));   % check input arguments
if nargin == 1    % n x 2 matrix
   if size(x,2) ~= 2
      error('input data must have two columns')
   else
      y = x(:,2);       % save columns as x,y vectors
      x = x(:,1);
   end
else    % two n x 1 vectors
   x = x(:);        % force into columns
   y = y(:);
   if ~isequal(length(x),length(y))    % same length ?
      error('input vectors must be same length');
   end
end

% need three or more data points
if length(x) < 3
   error('must have at least three points to fit a unique circle');
end

% solve linear system of normal equations
A = [x y ones(size(x))];
b = -(x.^2+y.^2);
a = A \ b;

% return center coordinates and circle radius
xc = -a(1)/2;
yc = -a(2)/2;
R  = sqrt( (a(1)^2+a(2)^2)/4 - a(3) );

% calculate residuals
if nargout > 3
   rres = R - sqrt((x-xc).^2+(y-yc).^2);
end
Appendix G.  VCM-based Tapping Actuator Design