

## Metrology and SPC

### ***Pre-lab Questions***

1. What is the resolution of the Ultra-Cal III electronic caliper?
2. What is the accuracy of the Ultra-Cal III electronic caliper?
3. What is the repeatability of the Ultra-Cal III electronic caliper?
4. What is the difference between accuracy, resolution, and repeatability?

### **Purpose**

- To introduce fundamental concepts in metrology and statistical process control
- To familiarize students with common metrology tools, such as dial calipers and coordinate measurement machines

### **Learning Objectives**

Upon completion of the laboratory, the student will be able to:

- use a caliper properly so as to make repeatable single-point measurements on physical artifacts to within the stated accuracy and resolution of the caliper
- interface a caliper via RS232 cable and operate software to enable measurement data to be recorded via computer
- explain the limitations of single point measurements in assessing the geometry of physical artifacts
- gather measurement data and manipulate it to produce an  $\bar{X}$  and R chart for assessing statistical process control
- assess whether or not a process is “in control” or “out of control” given data from  $\bar{X}$  and R charts

### **Components**

<u>Qty.</u>	<u>Item</u>
1	Fowler Ultra-Cal III electronic caliper, 6 in. (cat. no. 54-100-333)
1	Simplex RS232 connection kit (cat. no. 54-100-333)
1	PC with Microsoft Excel (or equivalent spreadsheet software)
1	Centerless ground pin kit

### **Introduction**

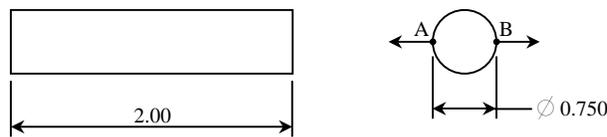
#### **Metrology**

The ability to *measure* physical quantities, such as length, time, force, etc. is of fundamental importance in everyday life, and especially in engineering, manufacturing, and science.

The science of measurement is called ‘metrology’. Of particular importance to the mechanical engineer is *dimensional* metrology, which addresses processes for determining the

linear and angular quantities of machine parts or their features [Farago, 1994]. In order for products to function properly, their component parts must meet dimensional requirements as specified on engineering drawings.

One of the most common dimensional or geometric characteristics is that of ‘size’. We say that a feature of a part has size when, for every point on the feature, there exists an opposed point on the feature and these opposed point pairs have collinear opposed unit normal vectors [Tandler, 2001]. A unit normal vector is a vector of length one unit (inches, miles, microns, whatever) that is perpendicular to a surface. For example, consider the drawing of a cylindrical pin shown in Figure 1. Pick any point on the cylindrical surface, and there will be an opposed point on the cylindrical surface that has a collinear opposed unit normal vector, e.g., points A and B below. A feature with size is denoted on an engineering drawing with a *double-ended arrow* and a nominal dimension (and sometimes a tolerance).



**Figure 1** Cylindrical pin drawing. The cylindrical feature of the pin is a feature with size, because there are opposed point pairs that have opposed unit normal vectors. A feature of size is denoted on an engineering drawing with a double-ended arrow and a nominal dimension (and sometimes a tolerance). Note that the slab-like feature consisting of the material between the two planar faces of the ends of the pin is also a feature of size.

Consider a circular cone. **Is this a feature with size?** Justify your answer.

A common tool often used for making size measurements is the caliper. (However, see the note at the end of these guidelines!) The caliper consists of one fixed jaw, one movable jaw, and a means to indicate the distance between the jaws. Long before the advent of microelectronics, calipers used a graduated scale on the fixed jaw and an index mark with an amplifying scale called a “vernier” on the movable jaw. Dial calipers came later, where the vernier scale was replaced with a mechanical, rotary dial that would indicate the measurement value between the major index marks on the fixed jaw. Now, electronic calipers are very popular, because they have user-friendly digital readouts, the ability to display the measurement in metric or customary units, etc.

This laboratory experiment will use an electronic caliper that also can be interfaced to a computer to record the measurement values. Figure 3 shows a model similar to the one you will use.

It is important to keep in mind that the instruments you will use in this experiment are *precision* measurement tools. It almost goes without saying that you need to treat them with care and use them properly. Please set them down gently, and always use a light touch when handling them. This is especially true when closing the jaws or making a measurement. Just a very *slight* force is all that is needed when closing the jaws.



**Figure 3** Electronic caliper. This model uses a capacitive sensing approach to measure the distance between the two jaws. It also can be interfaced to a personal computer using an RS-232 cable, so that measurements can be recorded automatically.

### Statistical Process Control

Statistical Process Control (SPC) is defined as:

“a method of monitoring, controlling and, ideally, improving a process through statistical analysis. Its four basic steps include measuring the process, eliminating variances in the process to make it consistent, monitoring the process, and improving the process to its best target value.” [NASA, 2002]

SPC is used extensively to monitor, control, and improve manufacturing processes. The usual goal in any manufacturing process of a particular item is to make each item like another with little variation. Variation is inevitable in any manufacturing process, however the quality of a manufactured item generally improves as the variation about a target value (usually the center of the specification limits) decreases. As an analogy, suppose you are riding in bus on the freeway. Where and how would you want the driver to drive the bus? Weaving around within a lane? Hugging one of the edges of the lane? No, for safety’s sake, most people would prefer the driver to keep the bus steady, right in the middle of the lane. Thus one might judge the quality of bus drivers by how well each keeps the bus in control within the lane. A ‘higher’ quality driver would keep the bus more centered in the lane with less weaving than a ‘lower’ quality driver. The same concept applies to manufactured items.

Consider a centerless grinding process that is supposed to grind cylindrical pins to a diameter of  $0.750 \pm 0.001$  inches. The target (or nominal) size is 0.750 in. The largest the pin diameter could be would be 0.751 inches (called the “Maximum Material Condition, MMC for short). The smallest the pin diameter could be would be 0.749 inches (called the “Least Material Condition, LMC for short). If we periodically select samples from the process (say a set of 4 pins take from the grinder every hour) and measure their diameter, we would say that the process is in “statistical *control*” if over some reasonable period of time, the average diameter of each set of 5 pins hovers around a constant value (for example, the middle of the tolerance zone, 0.7500 in.) and if the variability in the diameter within each set of 4 also is relatively stable around some constant value (for example, 0.00023 in.)

It turns out that the averages of samples (e.g., the averages of diameter measurements from sets of the 4 pins from the example above) tend to follow a Gaussian (normal distribution). This is called the Central Limit Theorem. [If you remember from statistics, a normal distribution can be described by its central tendency (i.e., its average) and its variability (i.e., its standard deviation)]. A clever guy at Bell Labs in the 1920’s, named Walter Shewhart, took advantage of the consequences of the Central Limit Theorem and devised a simple charting scheme to track the behavior of a process. The charts Shewhart developed are called ***X bar*** and

**R-charts.** X bar charts are used to track the averages of samples, and R-charts are used to track the ranges of samples. (The range is a measure of variability within a sample, and is defined as the difference between the maximum and minimum measurements in a sample). Here is a simplified explanation of how Shewhart's charts work in determining whether or not a process is in control. For a normally distributed variable, 99.73% of its values will fall within a  $\pm 3\sigma$  range centered around the population mean. Thus, a value of the variable that falls outside the  $\pm 3\sigma$  range will occur relatively infrequently. Since the sample averages for a process variable are normally distributed according to the Central Limit Theorem, if we get a sample whose average falls outside of the  $\pm 3\sigma$  limits for the population of sample averages, or exhibits some other non-random behavior, we should take notice and investigate what may have changed in the process to cause this event. This is what the X bar chart addresses. The R chart tracks variability in the process variable. If we start to see the range of samples crossing a calculated upper or lower control limit or exhibiting some other non-random behavior, we should take notice and investigate what may have changed in the process to cause this behavior.

In this laboratory experiment, you will construct X bar and R-charts for the diameter of a cylindrical part that was produced on a centerless grinding machine. Based on your results, you will make judgments on how well the grinding process is in control.

## **Procedure**

### **Group Formation**

1. Divide yourselves into 5 lab groups. A group must consist of no less than 2, but no more than 4 people. Depending on the size of your lab section, you may need to be flexible regarding the number of people in your group. Smaller is better, because you will learn more.

### **Familiarization with the Operation of the Caliper**

2. Hold the caliper by placing the palm of your right hand over the scale on the rectangular beam and wrapping your fingers around it. Place your thumb on the small wheel mounted on the movable jaw. Roll the wheel with your thumb to move the movable jaw. Notice that when you move the jaw away from the fixed jaw, a thin rectangular piece attached to the movable jaw protrudes out the end of the beam (also shown on the right side of Figure 3). This thin rectangular piece can be used to make depth measurements, for example, the depth of a blind hole. Referring to Figure 3, the lowermost jaws are used to make 'outside' measurements, while the smaller uppermost jaws are used to make 'inside' measurements, e.g., the diameter of a hole.

Turn on the display by pressing and releasing either of the two buttons, MODE or SET. There are two lines to the display. The upper line displays the measurement, while the lower line displays three things: the measurement units, whether the measurement is being held (denoted by the letter "H"), and the measurement mode, relative (REL) or absolute (ABS).

To turn off the display, press and hold the SET button for about 2.5 seconds. Turn off the display when you are not using the caliper to save battery life.

We are going to make absolute readings in customary (inch) units, so make sure that the second line of the display shows INCH and ABS. If it is reading in millimeters, press the MODE button three times, until the display says, "Unit", then press the SET button once to

change from MM to INCH. If the display shows REL on the second line, press the MODE button twice, until the display shows “rEF”, then press the SET button once to change to ABS.

It is very important to know and set where “zero” is *before* you start taking measurements. It is possible to set zero at any relative location of the jaws. In other words, the jaws don’t have to be touching each other to have the display read “zero”. In fact, the caliper resets zero when you turn it on. To set zero to be when the jaws are closed, you can either close the jaws, *then* turn the caliper on, or with the caliper on, close the jaws, press the MODE button once (the display should read SEt), then press the SET button once. **IMPORTANT NOTE:** to make reliable measurements, the jaws of the caliper must be clean and free of any particles. If in doubt wipe them with a soft cloth, or your shirt, or a clean finger. Once again, when you close the jaws, do so with a very light touch.

### Interfacing The Caliper To The Computer

The type of caliper we have interfaces to the computer via an opto-RS232 connector.

3. Make sure that the opto-RS232 cable is connected to one of the serial (COM) ports on the computer. The other end of the cable is a T-shaped plastic piece with a red LED that should be lit if the other end of the cable is connected to the computer and the computer is on. The T-shaped plastic part fits into a slot just above the Fowler sylvac label on the movable jaw. There is a dust cover above the label that must be removed before the cable end can be inserted in the slot (Please put the dust cover in a safe place, so it doesn’t get lost!). In order to function properly, the LED must shine *toward* the horizontal beam.
4. After connecting the cables, run the GageWedge program. This program handles the serial interface, and allows the caliper to send the currently displayed reading to any Windows program.
5. Make sure that the caliper is displaying a reading. Start Excel, and verify that the reading is transferred to a cell when the SET button is pressed.

### Practice Measurements

6. Measure the thickness of one page from the experiment guideline sheet. Input this value to the spreadsheet. How does this compare to the thickness of a page from your textbook?
7. Measure the diameter of a hair. Input the value to the spreadsheet. What is the range of hair diameters taken from each of your lab partners? Input these values on your spreadsheet.

### Creating the Control Charts

Each lab group should get its own set of 20 pins, that each have an alphanumeric code number written on one end. So, one group should the A set: 5 sets of 4 pins marked “A1 – A5”; the next group should have the B pins, “B1 – B5”, etc. Assume that each of the sets of pins, A – E represent samples taken off the centerless grinder over one day’s worth of production. Thus the pins in samples A1-A5 are samples taken earlier the day, and the pins E1-E5 were sampled later in the day. Each lab group is responsible for gathering the X bar and R data for their five samples (per the instructions below), and then as a class, each group will have to share its results in order to assemble the complete X bar and R charts and assess how well the process is in control.

8. Build an Excel spreadsheet with the cells and columns as shown below in Figure

9. Measure the diameters of the pins in your set, and enter the values in the spreadsheet using GageWedge. ;**IMPORTANT!** Take care to *maintain* the order of the samples as you enter the diameters in the spreadsheet. For example, if you have the A-set of pins, the measurements in the first column of your spreadsheet must only be for those 4 pins marked ‘A1’, the measurements in column 2 must be for those pins marked ‘A2’, and so forth.
10. Calculate the average and range for each sample. Remember that the range is the difference between the maximum and minimum values in the sample. (Make it easy on yourself, and use the AVERAGE(), MAX(), and MIN() functions.)

<b>Put the Title of Your Chart Here</b>					
Put the date here					
Put group member names here					
	Put the letter of your pin set here				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Piece no.	Diam., in.	Diam., in.	Diam., in.	Diam., in.	Diam., in.
1	0.4920				
2	0.4900				
3	0.4940				
4	0.4940				
Average=	0.4925				
Range=	0.0040				

**Figure 4** Spreadsheet for sample data. Enter your data into an Excel spreadsheet with GageWedge using this format. It is extremely important that you enter the data correctly into the spreadsheet. For example, if the letter of your pin set is D, then the column labeled ‘Sample 1’ must contain the measurements for pins marked ‘D1’, and likewise for the other columns.

11. Share your results with your classmates, and add to your own spreadsheet the data from all the other groups. ;**IMPORTANT!** Add the other groups’ data in such a way that the data sets A - E are in *alphabetic order* from left to right in your spreadsheet, i.e., the data for set A first, then set B, etc.
12. Calculate the average of all the sample averages (i.e., use the AVERAGE() function across the row called ‘Average’. Label this value  $\bar{\bar{X}}$ ).
13. Calculate the average of all the ranges (i.e., use the AVERAGE() function across the row called ‘Range’. Label this value  $\bar{\bar{R}}$ ).
14. Plot all 25 sample averages on a ‘Line Chart with Markers Displayed’. Thus you should have a single line consisting of 25 data points from the row labeled ‘Average’. Title this

chart, “**Xbar Chart for Pin Diameter**”. Label the vertical axis of your chart, “**Diameter**”, and the horizontal axis, “**Sample Number**”.

15. Add to this chart the two data series calculated from:

Upper Control Limit

$$UCL_{\bar{x}} = \bar{\bar{X}} + A_2 \bar{R} \quad (1)$$

where  $A_2=0.730$  for a sample size of 4, and

Lower Control Limit

$$LCL_{\bar{x}} = \bar{\bar{X}} - A_2 \bar{R} \quad (2)$$

Note that the UCL and LCL are constants, so the lines they represent will be horizontal on your X bar chart. You can hide the markers, since they are horizontal lines.

16. Add to this chart a data series representing  $\bar{\bar{X}}$ . This will also be a horizontal line.

17. Make a new ‘Line Chart with Markers Displayed’. Title this chart, “**Range Chart for Pin Diameter**”. Label the vertical axis of your chart, “**Diameter**”, and the horizontal axis, “**Sample Number**”. Plot all 25 values from the row labeled, ‘Range’ on this chart.

18. Add to this chart the data series calculated from:

Upper Control Limit

$$UCL_R = D_4 \bar{R} \quad (3)$$

where  $D_4=2.28$  for a sample size of 4.

19. Add to the Range chart a data series representing  $\bar{R}$ . Again, this will be a horizontal line, so no point markers for it are needed.

### Interpret the Control Charts

Control charts are a window into the understanding what is happening with the process. A ‘stable’ process is one where the plot points *fluctuate* around the centerline (i.e.,  $\bar{\bar{X}}$  for the X bar chart and  $\bar{R}$  for the R chart). Points that fall outside the control limits or unique patterns (i.e., non-random behavior) of points indicate that the process has gone out of ‘statistical control’ and further investigation as to the cause(s) is warranted [Cullen, 2000]. Some patterns to look for are:

- Several (i.e., like 5 or more) consecutive points on the same side of the centerline (this is called a ‘run’)
- A trend (either up or down) to the points within the control limits
- A periodic pattern within the control limits

20. Look at the X bar and R charts and discuss:

- a. **For the time period represented by your group’s set of samples, was the process in control?** Explain your answer from the behavior shown on the charts. **If the process is out of control, what may have caused it?**

- b. Over the entire day describe what is going on with the process. **Where is the process in control, out of control (and how can you tell?), and what may be causing any observed non-random behavior?**

### **Additional Questions**

1. If the diameter of a cylindrical pin is measured using a caliper to be 0.5000 in., will it always be able to fit through a hole measuring 0.5060 in.? Explain your answer.

### **References**

Cullen, C. (2000) "SPC for Long&Short Production Runs," course notes, International Quality Institute, [www.I-Q-I.com](http://www.I-Q-I.com)

Farago, F. T., Curtis, M. A. (1994) Handbook of Dimensional Measurement, Industrial Press, New York.

NASA HQ Library (January 12, 2002) <http://www.hq.nasa.gov/office/hqlibrary/ppm/ppm31.htm>.

Tandler, W. (February 2001) "The Little Encyclopedia of Geometric Dimensioning and Tolerancing," Multimetrics, Inc., Menlo Park, CA, [www.multimetrics.com](http://www.multimetrics.com)

### **Note on Size Measurements With Calipers**

It is very easy to get into serious trouble by using calipers to assess the size of a feature that does not have perfect form. A manufactured part, as opposed to a CAD model, will always have imperfect form. Therefore, it is extremely important to understand the limitations of the caliper in assessing size. We will demonstrate the caliper's limitations in assessing size by an example during the lab session.