

## Making Sense of Accuracy, Repeatability and Specification

### Introduction

Accuracy and repeatability contribute to successful dispensing system performance. There are many factors to consider when evaluating these capabilities. Particularly when comparing published specifications for multiple systems. It's common for suppliers to define accuracy and repeatability specifications in different ways. These varied definitions can lead to an incorrect comparison or assessment of a system's ability to perform application requirements.

### Accuracy vs. Repeatability

Accuracy and repeatability measures are commonly used to express dispensing system performance. Unfortunately, these terms are often confused or misunderstood.

Accuracy (Figure 1) is a measure of how close an achieved position is to a desired target position.

Repeatability (Figure 2) is the measure of a system's ability to consistently achieve identical results across multiple tests. The ultimate goal is to have both a highly accurate and highly repeatable system.

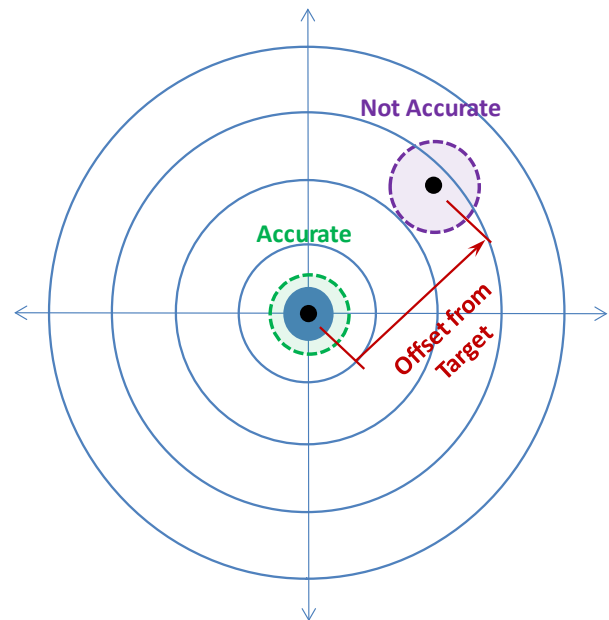


Figure 1. Accuracy

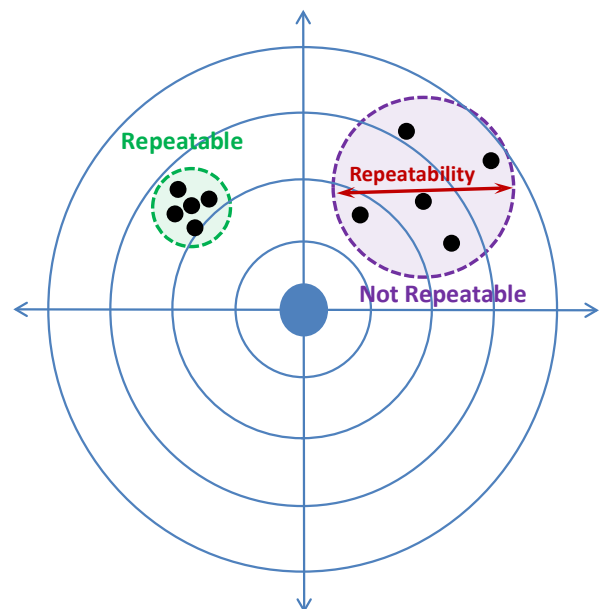


Figure 2. Repeatability

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Repeatability is often expressed as the range (variation) of measurements achieved for multiple test points under consistent test conditions. Figure 2 illustrates examples of repeatable and non-repeatable processes. Thus, for the purposes of specifications, achieving smaller repeatability numbers is better because it indicates tighter groupings or a smaller range within the test data distribution. Repeatability differs from accuracy in that it is concerned with variations in achieved results relative to each other within a given sample size.

As discussed, accuracy is commonly used to express dispensing system performance. Specifically, dot placement accuracy (DPA) and line path accuracy (LPA). To achieve DPA, a system must dispense a dot in an exact target location. To achieve LPA, which is more challenging, a system must put down precise lines of fluid without deviating from the programmed path – including straight lines and around corners as shown in Figure 3. To determine dispense accuracy, the test offset error between the achieved result and the target (ideal) are measured, as shown in Figure 1. A smaller test offset error means a system is more accurate. The determination of accuracy should be based on a large sample of test results, not on a single test. As such, it is common practice to use the average (mean) error to express the accuracy across an entire distribution of test data.

Accuracy and repeatability are closely related but are two independent specifications. It is possible for a system to be repeatable but not accurate, and it's also possible for a system to be accurate but not repeatable. As previously mentioned, an ideal system is one that is both accurate and repeatable, as illustrated in Figure 4.

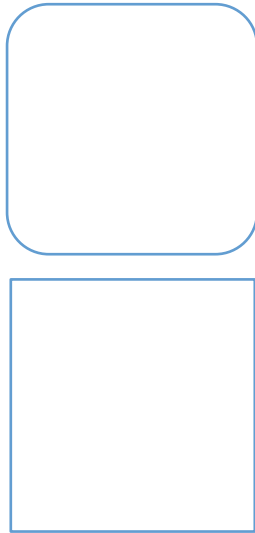


Figure 3. Line path examples

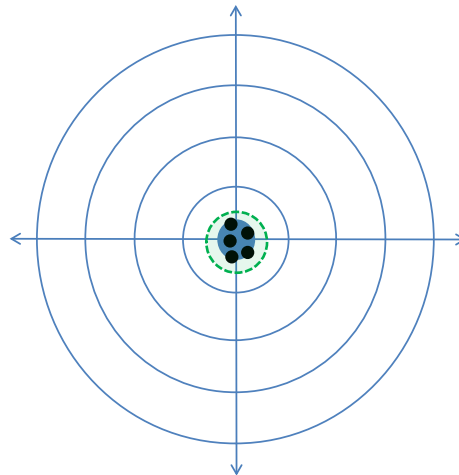


Figure 4. An accurate and repeatable process – DPA

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Accuracy and repeatability need to be placed in context to a specification to be meaningful. Typically, accuracy and repeatability specifications are bounded by an Upper Specification Limit (USL) and a Lower Specification Limit (LSL). Standard deviation,  $C_p$  and  $C_{pk}$  describe how accurate and repeatable a set of test results are contained within the USL and LSL.

The standard deviation,  $\sigma$  (sigma), is a measure of the spread of the data around the mean. Standard deviation is calculated based on the following formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{(n-1)}}$$

Where  $n$  = the number of samples in the data set,  $x_i$  is the value of a given data point within the data set, and  $\bar{x}$  is the average value of the data set.

In a normal population of data points (See Figure 5), 99.7% of all test data will fall within  $\pm 3\sigma$  of the mean. In a sample size of 1000, for example, 3 samples could fall outside the  $\pm 3\sigma$  range and those would be considered outliers or rejects (e.g. yield loss). In some cases, these outliers may be expressed in a parts-per-million (PPM) statistic to shed light on potential yield loss related to the dispensing process. For a  $\pm 3\sigma$  process, this would equate to up to 3,000 PPM that could fall outside the specification range.

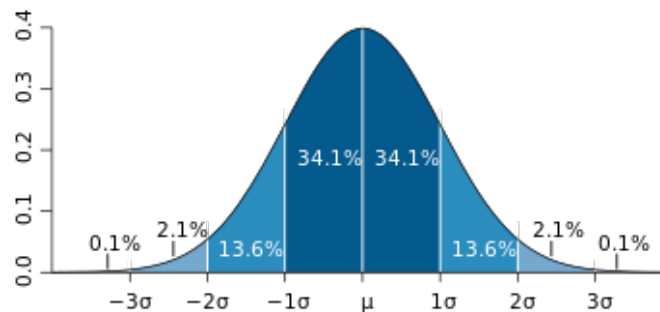


Figure 5. A normally distributed data set with % of data at varying sigma levels.

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$C_p$ , known as process capability, indicates the spread of data relative to a specification range.  $C_p$  is calculated based on the following formula:

$$C_p = \frac{USL - LSL}{6\sigma}$$

In general, a process is said to be capable or in control when the  $C_p$  value is  $\geq 1.0$ . Therefore, that value is used for this discussion. Using  $C_p$ , however, assumes that the center of the data set falls at the midpoint between the USL and LSL. So, it is possible to have a highly repeatable process (low variation, tight distribution of data) but be completely off target (poor accuracy) as in the case of the left group of data points in Figure 2.

$C_{pk}$ , by comparison, considers both the spread of data within the specification range and the location of the center of the data relative to a target that is midway between the USL and LSL.  $C_{pk}$  is defined with the following formula:

$$C_{pk} = \text{minimum of } \left[ \frac{USL - \bar{x}}{3\sigma}, \frac{\bar{x} - LSL}{3\sigma} \right]$$

Where  $\bar{x}$  = mean of the sample data.

Put another way,  $C_p$  is an indicator of how repeatable a system performs, and  $C_{pk}$  indicates how accurate and repeatable the system performs relative to the USL and LSL. The process is said to meet specified capability when the  $C_{pk}$  value is  $\geq 1.0$ .  $C_p$  and  $C_{pk}$  values  $\geq 1.0$  correlate to a  $\pm 3\sigma$  value as discussed above. It's important to note that some manufacturers, for instance in the automotive industry, require  $C_p$  and  $C_{pk}$  values = 2.0 which correlates to a  $\pm 6\sigma$  value. Conceptual differences between  $C_p$  and  $C_{pk}$  are shown in Figure 6. It is possible to have  $C_p > 1$  (good repeatability) but  $C_{pk} < 1$  (poor accuracy) if the distribution of data is not centered at target.

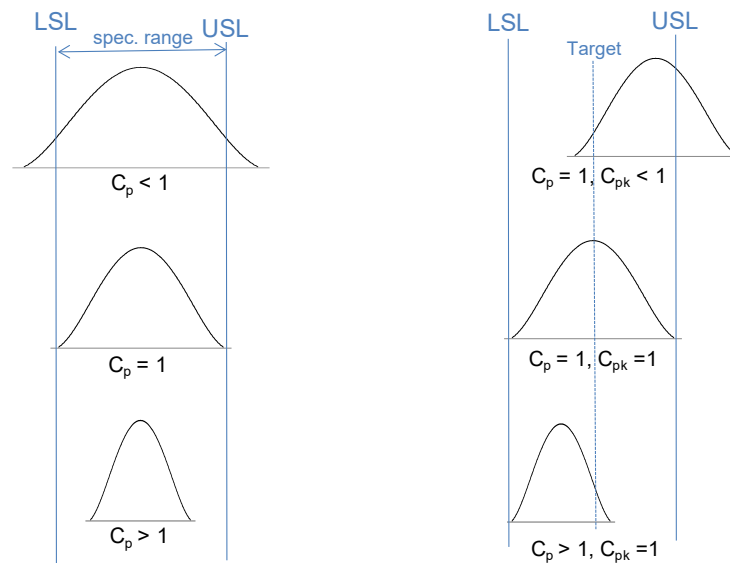


Figure 6. Difference between  $C_p$  and  $C_{pk}$

## Accuracy, Repeatability and Specifications

Dispensing system design, in addition to accuracy and repeatability, contributes to overall system performance. When you're comparing performance specifications for different systems, it's important to understand what a specification is based on. For example, is a given DPA or LPA specification based on "dry" or "wet" dispense results?

## Motion System

The motion system presents two main factors for consideration – positioning accuracy (resolution) and dynamic or static conditions during testing.

Resolution, also called step size, is the smallest possible change in movement that a motion system can detect (Figure 7). Resolution is determined by motion system capability and encoder feedback. Unfortunately, resolution is typically measured at the encoder, which only indicates the current positions of the encoder scale and read head. Other factors such as the encoder mounting location relative to the dispense valve, thermal expansion, the frequency of encoder readings, friction, and hysteresis (backlash) are used to determine *the actual* motion system position at any given instant. The resolution of a system can indicate the lower boundary of repeatability, and better resolution generally results in better accuracy. However, resolution alone does not provide an accurate indication of system performance.

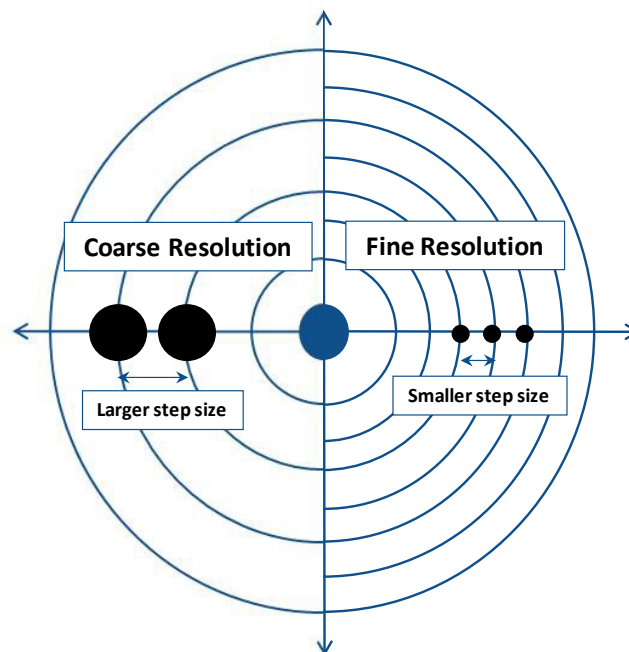


Figure 7. Resolution

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The dynamic or static condition of the motion system becomes important when examining the position of the dispense valve at the instant of dispense. A system can be considered to be in a static condition when it has fully stopped moving and any residual oscillations from a prior move have died out. In a static condition, the encoder read head position should closely correlate to the dispense valve position as there should be little to no relative motion between the two positions. However, settling time is needed to achieve such a condition, which could impact productivity (UPH). If the system dispenses before all oscillations have completely died out, or the system is moving (dispensing on-the-fly), there will be some induced error between the read head and dispense valve positions. This error will then translate to some level of degradation in dispense accuracy.

### Dispense Valve and Fluid Type

The dispense valve and fluid type also affect accuracy and repeatability specifications. Valve type can affect the operation of the dispensing system as a whole and thus impact dynamic or static dispensing conditions. The mass of the valve and the fluid reservoir will affect the inertia of the system. Additionally, for valves or applications that require a much tighter dispense gap between the substrate and the dispensing tip, the system must move to the X-Y position and then down to the Z position. The pause to allow motion in the Z-axis acts as an artificial settling time and can improve dispense accuracy. Similarly, the gap between the dispense tip and the substrate can create a minor offset in the fluid position, if the fluid does not eject vertically down from the dispense tip to the substrate. In such a case, having a larger dispense gap introduces a larger X-Y error.

Interaction between the dispensed fluid and the substrate can also affect measurement results. For example, underfill fluids are designed to flow out and tend to spread out on a substrate surface into irregular dot shapes, as opposed to a surface mount adhesive, that retains its shape and stays in one place after dispense. This fluid-surface interaction and post-dispense motion can make it difficult to determine the actual dispense location, and the determination of a fluid dot centroid location can induce additional error. These factors must be accounted for during wet dispense performance testing. If done correctly, the resulting wet dispense will provide you with the most realistic representation of system performance and the system's ability to meet your application requirements.

### Vision System

Accurate fiducial targeting is another important factor that contributes to overall system accuracy. Most automated fluid dispensing systems use some type of vision system to locate target fiducials and identify where to dispense on the substrate. A vision system reduces the dependence on motion system accuracy and compensates for slight shifts in part orientation or location – which can occur when a substrate is placed in the system or during upstream production processes.

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In most cases, a vision system is carried on the same moving gantry as the dispense valve. This means the vision system and the valve are subject to the same errors that affect positioning accuracy, and the coordination between these systems has an overall effect on wet accuracy. The frame-capture time, and the correlation of a frame capture to a specific position in the dispenser's X-Y motion area, creates similar issues to those previously mentioned in the motion system section. In most cases, the camera and dispense valve are mechanically offset from one another. In such cases, the system software must calibrate the distance between these two positions. Creating an offset error if the two positions vary relative to each other or if the calibration is too coarse (see Figure 8).

In addition, the pixel-to-micron resolution of the vision system affects the system's ability to locate a fiducial feature. The vision system algorithm must consistently locate a target position within a captured image to determine where to dispense fluid. Substrate and fiducial imaging also requires adequate lighting to create sufficient contrast in a captured image. This allows the software to correctly identify the fiducial position. Therefore, even with perfect motion system accuracy, if the vision system does not properly target the correct position, the total system accuracy can suffer.

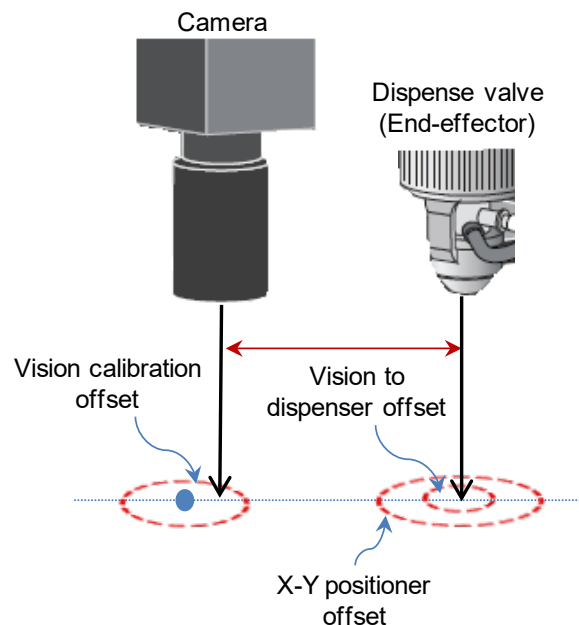


Figure 8. Camera to dispense valve offset

## Interpreting Accuracy and Repeatability Specifications

When evaluating specifications, it's important to have clear understanding of the method used to obtain dispensing system performance results. Comparing data obtained under different conditions can make specification comparison difficult, and it can also lead to incorrect conclusions.

For example, artificially high positioning accuracy and repeatability could be achieved when the equipment is operated below normal speed. In another example, one specification could be referencing dry dispense performance while a comparable specification is referencing wet dispense performance. With so many factors influencing how specifications are characterized, it is important to understand the test conditions and how a specification was created and measured.

Consider the following:

- Does the specification represent a best-case scenario or a normal operating condition?
- What is the data spread of the claimed specification?
- Is the specification achieved at the positioning sensors or at the fluid dispense location?

True system positioning specification is captured at the fluid dispense location, and not at the positioning sensors. True system positioning considers factors beyond X-Y positioning accuracy and repeatability. It also takes into consideration the effects of calibration, vision system resolution, and the offset between the vision system and the actual dispensing position. Figure 9 illustrates total system capability at the fluid dispense location. The final system performance reflects the accuracy (based on the mean of the sample set) and repeatability to achieve results around the mean position.

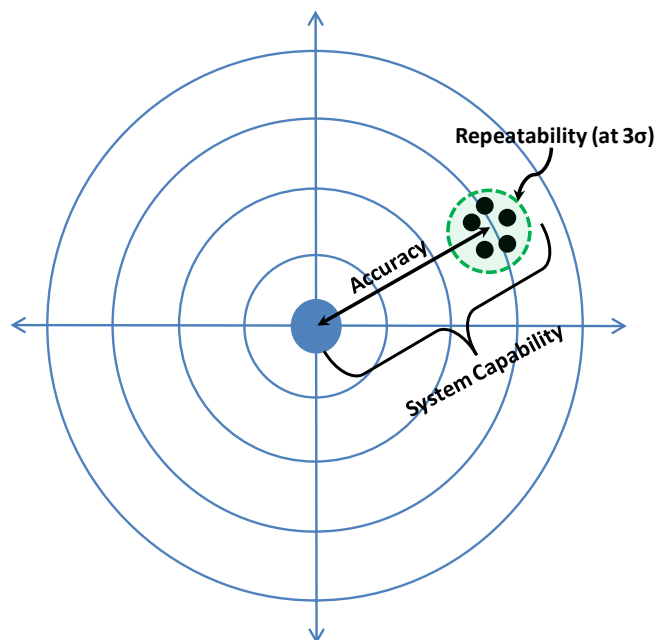


Figure 9. Total system accuracy



## Conclusion

Accuracy and repeatability are important factors in determining fluid dispense capability. They are often the key attributes that determine whether equipment can meet target process parameters. However, claimed specification numbers are highly dependent on underlying conditions. Therefore, when comparing specifications between two systems, it is crucial to understand the complete story behind the specification. It is always recommended to check the conditions under which the claimed accuracy and repeatability are specified. With that knowledge, you can make a fair comparison between different systems.

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**North America Headquarters**  
2747 Loker Avenue West  
Carlsbad, CA USA 92010-6603  
Phone: +1.760.431.1919  
Email: [info@nordsonasymtek.com](mailto:info@nordsonasymtek.com)

