Poor Metrology: The Hidden Cost

Michael Cieslinski
Panasonic Factory Solutions Company of America
Buffalo Grove, IL

Abstract
Doing more with less has been the standard operating procedure in manufacturing over the past ten years. Everyone is looking for areas where they can cut corners, maintain quality, and improve productivity. Many placement machines have the ability to self-calibrate and provide capability numbers. In an attempt to save resources, many manufacturers are using these values in place of true capability studies. This practice prompts two questions that need to be answered: "How valid is the internal measurement?" and "If it is not valid, is there still value in using it?" The simple answer to these questions is that internal calibrations are not valid to predict yield, but do have value for the user. This paper compares and contrasts acquiring a Cpk value from an external metrology system versus one from an internal system. It also provides evidence that an external system is necessary to run a true lean six sigma facility.

An external metrology system provides the capability to truly reduce the cost of poor quality and increase profits. Included case studies show the improvements a user will see in metrics like DPMO and first pass yield when using an external metrology system versus only using an internal calibration system. These studies also show how improving DPMO and first pass yield will actually reduce manufacturing costs.. Increased profitability is what all factories are trying to achieve, but it can be diminished due to potentially misleading reports provided by internal calibration systems. In many companies the cost of this mistake is unknown to management— consequently perpetuating with every new production run.

Introduction
The lack of proper metrology inflates the cost of poor quality, so it is important to know how metrology is defined and how to perform it correctly. Understanding why internal calibration systems and AOI don't qualify as metrology is also important. Once a clear understanding is established, the true value of metrology can be revealed and the benefits tabulated.

Definition of Metrology
One of the key problems when talking about metrology is that not everyone is clear about the definition. People make the common mistake of using the term interchangeably with measurement. Under this definition any tool that gives measurement results provides good data for metrology, but this could not be further from the truth. Wikipedia defines metrology as "the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties." [1] This shows that the key aspects to metrology are traceability and determined uncertainties of the measurement results. When metrology is performed properly, values can be compared to previous measurements or measurements taken in different locations anywhere in the world, making metrology a valuable asset.

Several things must be done to ensure the measurements taken are actual valuable metrology and not just numbers. The three types of measurement errors are: repeatability, reproducibility and bias. Repeatability of a measurement system is classified by the short term variation of the measurement equipment. It answers the question, with all environmental variables constant, "How repeatable are the numbers?" These variables include operator, temperature, humidity, artifacts and measurand. Reproducibility looks at long-term variation, which has an effect when there are changes to the environmental variables. So reproducibility studies look at different operators, temperatures, and humidity to see if the data can be reproduced under different conditions. Since these variables will not be maintained exactly over time, the measurement process will experience some of these errors as time goes by. The user must try to limit these variables as much as possible to maintain good reproducibility. The final area is known as bias, which can be defined as the deviation from the known value to the measured value. Determining the known value is where traceability comes into the metrology equation. The known measurements come from standards/artifacts that are compared to other known standards; this process goes all the way back to the standards that are kept at the International Bureau of Weights and Measures [2]. With each comparison the measurement uncertainty is passed on to the next measurement and added into the final equation of the total measurement uncertainty. When inspection machines are calibrated these measurement uncertainties are passed to that inspection machine and subsequently to all the measurements taken on that machine.

Figure 1. International Bureau of Weights and Measures [2]

These uncertainties combined with the Gauge Repeatability and Reproducibility (GR&R) variances give the user a level of confidence in their inspection machine. This confidence comes in terms of a process-to-tolerance ratio (PT ratio) which can range from 10% (excellent) up to 25% (acceptable) depending on the application. As part of achieving the 10-25% PT ratio the inspection systems needs to be 10x the resolution and accuracy of the process it is trying to measure. This is known as the processes discrimination. Without this increased resolution and accuracy the variation reported may just as likely come from the inspection machine as the process.

In the electronics industry ,inspection is typically performed with an optical coordinate measuring machine (CMM) as the primary way to determine SMT machine placement accuracy. The CMM is calibrated using standards/jigs certified by the National Institute of Standards and Traceability (NIST) in the USA or other standards agencies such as the National Physical Laboratory in the UK. All of these national institutes trace their standards back to the International Bureau of Weights and Measures in Paris, thus allowing every CMM to be calibrated to the same standard and making a measurement of 0.005 mm reproducible anywhere in the world to some level of stated uncertainty. While most CMM suppliers suggest annual recalibration to maintain accuracy and limit bias, the user is responsible for performing a GR&R on the products to be inspected. The user must define the recognition of SMT placements when using an optical inspection machine by using CMM-supplied standard recognition tools to create custom algorithms. If the user defines these algorithms incorrectly the recognition will either not be repeatable or not be accurate. While the GR&R will determine if the user's defined recognition algorithms are repeatable, it won't determine accuracy. Special artifacts need to be created to determine if the algorithms are accurate. IPC9850 has a suggested accuracy board design with chrome representations of standard SMT components that can be used to determine bias. It also provides deviation from nominal locations so the algorithms can be tested over the entire range of their specifications. The chrome representations are certified by a lab to create the unbroken chain of comparisons. Without this type of artifact there is no way to measure bias of custom algorithms.

Internal Calibrations

In a perfect world, machine offsets would not be needed. All machine camera locations, spindle offsets, shaft rotation centers, and feeder bank locations would be exactly the same and precisely made to design. But everything has a tolerance, which creates the need for offsets to compensate for these deviations. To make things more complicated, placement machines have progressed over the past twenty years from simple single gantry/single spindle robots to much more complex machines that can have up to 20 gantries or over 68 spindles each. And with each spindle there can be multiple cameras, pickup locations, and rotations that all require their own offsets. If not for the invention of internal calibration systems, the vast number of offsets required would be unmanageable. These internal systems allow machines to set these offsets quickly and efficiently. In addition to self- calibration, many of these systems provide instant feedback to the operator in what appears to be capability data—such as Cpks.

The performance of internal calibration requires the combination of inspecting standard jigs and placing parts. Jigs calibrate internal sub-systems of a machine. A calibration system may run by picking up a jig with a spindle and then scanning it over a camera. Their location can be written as an X and Y offset. Then the nozzle can rotate and scan over the camera again to determine that spindle's center of rotation. That jig can then be picked up by another spindle and the process repeated. This allows the machines to set the relationships between different sub-systems to increase accuracy.

Most internal calibration procedures end with a user placing parts on a board and inspecting them with an internal camera to determine deviations from ideal placement. These measured values are then used to adjust the appropriate offsets internally. A second board can be run to test the effect. Many times these results are reported as a machine capability in terms of statistics such as means, standard deviations and Cpks.

Value of Internal Calibrations
The value of using internal calibration procedures is immeasurable—the first benefit being the simplification of the service process. In many cases, machine part replacement is as easy as disconnecting a few cables, loosening a few bolts, replacing a part, and then running the auto-calibration procedure. The ability to quickly calibrate a machine using jigs/internal calibrations allows a trained user to service his or her own machines. Correcting hundreds of offsets quickly without having to know anything about the machine's design is especially beneficial, making it possible for a maintenance technician to work on many different equipment types with minimal training.

Another benefit of internal calibrations is its repeatability. The technician's skill is no longer a deciding factor in how well the machine is calibrated. The machine calibrates itself once the process has started and does it the same way every time. This consistency is key.

Instant feedback is another important benefit. Many of the internal calibration procedures provide a capability number to quantify its success. When a mechanical system has problems, they manifest themselves in the form of high process variation. This means that if something is mechanically incorrect, the system will not be repeatable. Therefore the internal system's instant feedback of Cpk shows the system's repeatability. If the repeatability is determined to be very low the technician knows there is a mechanical problem with the machine. If the value is acceptable, then a technician will have fairly high confidence that the machine is mechanically correct. But the internal calibration system has no way to determine if it is accurate. Since these systems use the same drive systems to place and measure parts there is no way to determine the bias introduced into the measurement values. That means the capability numbers that are reported are meaningless in terms of statistics, but still remain valuable for indicating if the system is repeatable, even if the offsets are not ideal. Additional calibration using an actual metrology system can be necessary to achieve the highest level of performance.

Why Internal Calibrations Don't Qualify as Metrology
Traceability is key to the idea of metrology. The unbroken chain of comparisons give the user confidence in the numbers reported. Internal calibrations fail this primary metrology principle. since the placement machines are not certified with the same high precision jigs that inspection machines use for certification.

Internal calibrations cannot achieve proper PT ratios. When the same drive system controls placement and measurement it isn't possible to determine the source of any variation. If 0.025mm deviation is reported, it is just as likely that the machine placed the part perfectly and the 0.025mm variation is due to inspection error as it is that the machine inspected it perfectly and the 0.025mm is all placement error. In many cases internal calibration systems only provide data in terms of summary numbers like means, standard deviation, and capability. This doesn't allow for proper testing to be performed on the inspection capability of the system. Without individual data points for doing a GR&R, determining the repeatability error is impossible. Determining the reproducibility error would be difficult as well since these systems typically don't allow the user to change operators, board loading conditions, and other long term variation variables necessary to perform reproducibility tests. Using the same drive system to inspect what is placed also violates the inspection principle of having adequate discrimination for inspection. The best practice rule is that the inspection system should be 10x more accurate and repeatable than the process that is being measured. In this case it is 1-to-1—far below best practices.

Using the same system for inspection also risks the possibility that drive system problems will be masked. This means process problems will be hidden, which can cause yields to drop below the level predicted by the internal capability results. For example, all placement machines work with encoders (either linear or rotary), which act as scales to provide the drive system with distance moved. Essentially these encoders count lines. If an encoder is damaged, the scale will read more or less ticks over a given area and the machine will think that it has moved a different distance than it actually has. There is a chance that the damage may cause readings that are incorrect, but very consistent. If this happens, internal calibration numbers look much better than reality since the same damaged system that placed the part now inspects the part. For instance, if a system counted two extra tick marks when placing a part, the placement is two ticks less than ideal. And when that machine inspects that placement, it will count the same extra two tick marks and stop in the exact location of the placement. The machine will provide a measurement of zero deviation even though the part is actually off by two ticks. When this happens repeatedly the results reported by an internal Cpk can be grossly inflated. And this is just one example of how an internal system can hide or mask internal problems, affecting attempts at metrology.

Problems with internal calibration procedures are common across different platforms and brands of placement equipment. Some placement equipment platforms may have better internal calibrations than others, but all have some form of inaccuracies. As part of the information gathered for this paper, Panasonic platforms were tested along with many of their competitors. The one consistent fact between all the comparisons is that when a machine is calibrated with an internal system and then checked against an external measurement machine the reported capability on the external system will always be less than that reported on the internal one. Better systems will report Cpks closer to that of the external system, but this needs to be established on a machine-by-machine basis since an old machine of any platform may not provide the same results as a new machine of that same platform.

Using inflated capability numbers from internal calibration systems can lead to overconfidence in the system, wasting engineering time and causing long-term quality issues. As a real world example Company Y was using the internal calibration system of Placement Machine X. Company Y believes that when they received a Cpk of 2.0 from the internal system that Placement Machine X is placing accurately. When they start having quality problems with placements from Machine X, the technicians and engineers rule out the machine as the problem source due to that internal calibration report. Their short-term resolution is to adjust the CAD coordinates on Machine X by 0.200 mm to get the parts placed on pad. Engineering needed to investigate the validity of the CAD data and the programming process to try to determine the cause of the placement discrepancy. But for all that time spent researching no resolution was found except to continually adjust the CAD data. This solution eliminated the program portability which in turn put limits on Company Y's production. In addition to the inconvenience and wasted time, the quality coming from Machine X is not as good as it could have been since 0.200 mm is not a measured value but an estimate. Not until an external measurement machine was brought in to verify the process was it found that Machine X was consistently off 0.244 mm in the X direction while passing Cpk in Y and Theta. After increased cost to them in time, money, and quality, Company Y learned that using internal calibration results to eliminate the machine as a cause of variation in the process shouldn't have been done. Internal calibration results don't pass the rules for metrology so they can't be used to accurately predict yield or prove out a process.

Keys to Good Metrology

While it is clear that internal calibration systems don't qualify as true metrology, there still remains the question of whether all external measurement systems qualify. The answer is no. There are still a few key metrics that need to be taken into account to ensure the external, or offline, system qualifies. If these metrics are unchecked and the process' uncertainty is undetermined, it will remain unclear if the variation measured is from the placement or the inspection process.

If a user measures a board on two different external inspection machines and Inspection Machine A reports a 0.050mm shift, while Inspection Machine B reports a 0.089mm shift, how can the user know which inspection machine is correct? Moreover, if the user hadn't placed the board on the second inspection machine, there would have been no doubt over the first measurement. That is why the external inspection process needs to be qualified and the measurement uncertainty established.

Performing a Measurement System Analysis (MSA) is the standard way of determining what percentage of the total variation is from the inspection system versus the placement process. When done correctly the user can have confidence in the numbers reported by the inspection machine, knowing exactly what percent of the error is from the process. The first test of a MSA is to determine the system's repeatability and reproducibility. Table 1 provides examples of measurements of the same object taken by different operators. In this case, Kate is the most repeatable operator since she has the least variation between her measurements, but Sue and Mary are the most reproducible. This is not a good measurement system though. If Kate is measuring parts, there's consistency in the measurements, but as soon as Sue or Mary take over the measurement results will differ greatly and lead to doubt in the numbers. Just like before when data received from the inspection process is unclear as to whether the variation is from the process or the measurement the MSA is no good. Determining the measurement system quality can not be done by looking at any one data set. Only by setting up specific tests, can the error for the measurement system be qualified. In the SMT industry there are typically two test run to qualify inspection equipment, these are a GR&R and an accuracy test. In some cases reproducibility, repeatability, discrimination and bias can be determined in one test.

Table 1 – Repeatability vs. Reproducibility

		Operator		
Measurement		Sue	Mary	Kate
	1	4.1	4.4	3.1
	2	4.5	4.5	3.2
	3	4.3	4.2	3.2
	4	4.1	4.7	3.1
	5	4.7	4.1	3.2
	6	4.8	4.3	3.3

The first test done in a MSA is a Gauge Repeatability and Reproducibility (GR&R) test. The GR&R should be set up to test 2 - 3 operators measuring 20 - 30 parts 2 - 4 times each. Quantities can vary depending on the MSA chosen and the measurement process' variation source. Operator-dependant processes benefit from more operators in the test while processes with a component-related variation majority are better tested with more components. It's important to note that the components need to be representative of the entire population, covering the deviation range that could be seen during production. This includes parts that are out of specification. If a placement machine has specification limits of +/- 0.100mm but the deviations from that machine in production have been found to have a range of +/-0.120mm, the GR&R should use a board that has placements with a range of at least +/-0.120. If someone ran a GR&R using a board from a calibrated machine with placements ranging from +/-0.030mm the user would have no idea how the inspection system would handle parts near the edge or outside the specification range. The inspection process might be very repeatable when centered but may fail out near the specification limits. Finally, in systems with a variation majority that comes from measurement process repeatability, a better result can be achieved if the boards are measured additional times.

Another key principle of a good MSA is having the proper discrimination for the test. Discrimination is defined as the decimal places reported by the inspection equipment. A good rule of thumb is that the inspection system should have ten times the resolution of the production process specification. This means if the process specifications are +/-0.050mm the inspection machine should have specification limits of +/-0.005mm. The standard measure of discrimination is the number of distinct categories present during a GR&R test—with the number of distinct categories meaning a count of how many different buckets of information the inspection will group its results into. An example of this would be trying to measure people's weight on an industrial scale that reports weights rounded to the nearest hundred pounds. For the range of weights from 75-249 lbs there would only be two distinct categories:100 or 200. If a GR&R was performed on this inspection process the repeatability and reproducibility may be very good, but this system will fail its MSA since a lot of information about the population weighed is lost due to low discrimination capability. The AIAG Measurement System Analysis version 3 manual states that the minimum number of categories required to pass a MSA is five. To be excellent the GR&R for the system should have more than 10 distinct categories.

The final key metric in the determination of a good measurement system analysis is a measure of bias. Bias is defined as the difference between the measured value and the "true value". The "true value" can never be known exactly but is stated with a total measurement uncertainty. This measurement uncertainty is a combination of all the tolerances along the chain of comparisons that goes back to the golden standards at the International Bureau of Weights and Measures. The test to determine bias involves measuring a known artifact and determining the deviations. The artifact measured should simulate what is being inspected during the normal inspection process and should have its features certified by a lab to determine their true locations. When these features are measured by the inspection machine, the deviation from the "true values" are reported as their bias. In some areas these biases, along with the repeatability and reproducibility errors, are summed using the sum of squares to determine a total measurement uncertainty. While this practice is common in most other industries, it is not widely held in SMT.

Value of Metrology and SPC

Statistical process control (SPC) was started in the late 1920s but gained predominance in the 1960s with the purpose of improving product quality and, ultimately, drive down manufacturing costs . The key behind SPC is understanding a process' common cause variation and knowing when a special cause variation appears. Common cause variation is a normal variation with no specific cause and cannot be removed with simple changes to the process. Meanwhile special cause variation does have an assignable cause and can be fixed. SPC also allows the manufacturer to move to a predictive maintenance model, instead of a reactive one, where they can fix problems before defects are created, instead of stopping the process after defects are present.

Manufacturing cost improvements come from many factors, the first being defect reduction. Defect-related cost reduction comes from hard cost reductions in scrap rate, rework elimination, and diminished unplanned line downtime. Related soft cost savings include time that can be saved throughout many departments, such as engineering, quality, production, and maintenance, that spend time fixing quality problems instead of working on projects that make the company money. Conversely, troubleshooting defects' root causes without a clear understanding of what has changed and what is causing the variation is a large waste of time. If quality numbers are reported a shift or day after the production run, the people working on the problem don't have a good idea of the problem's cause since environmental variables have changed since the original problem. This means the same defects will probably return when that product is run again. The cost of poor quality is increased by this delay in problem solving. But when SPC is done properly there is access to data that shows what changed and when, allowing engineers and maintenance to schedule time to return the process to its original state and prevent defects.

Setting up a SPC system takes resources and discipline on the company's part. When it is not done properly it is a waste of time and money. Inaccurate data collected in a SPC process leads to wrong conclusions, making problems harder to solve and often resulting in increases in cost and downtime. Add the cost of maintaining these bad SPC systems to the cost of fixing those harder-to-solve problems and the cost of quality becomes extremely large. Wasted money due to bad metrology has left some manufacturers believing that SPC doesn't have enough benefits when compared to the cost. That could not be further from the truth—having good data and understanding the process is vital to remaining competitive in today's manufacturing environment. The key is having good data and that can only be done using a good, true metrology system.

Just recording any numbers that can be found because they are convenient or seem free of cost is what is done by many companies when they use internal calibration numbers to replace metrology systems. But that just inhibits the benefits of proper metrology.

Why Metrology is Done Wrong

Since SPC and metrology are part of a mature process started over 80 years ago, the assumption could be made that these quality tools are widely implemented across the SMT industry. But there are many companies that don't use SPC and metrology. Many take short cuts and think they are using it when they truly are not. So why does the proper implementation of these quality ideas often not occur?

The first reason is a lack of knowledge—not knowing the definition of metrology or how it is used in a SPC system. Thinking any machine that provides numbers is providing metrology data is one of the most common mistakes in the industry. This covers both internal calibration and AOI systems that provide some output of placement deviations. Why internal calibrations systems are not real metrology has already been covered here and many of the same reasons apply to AOI.

AOI systems don't have traceability of measurement uncertainties, nor are they able to distinguish a solder process from a placement process or a board variation, so they cannot know which caused a component to be skewed on a board. And since an assignable root cause cannot be determined, the deviation an AOI system reports is not useful for SPC in tracking machine capability. Most AOI systems will also fail a measurement system analysis in discrimination versus the process or in GR&R results being less that 25% of the process specification. Yet, with all of these negatives, manufactures want to use these systems as metrology because they already have them—no additional capitol equipment or labor needed. They do this without the knowledge that these systems don't provide true metrology so they miss out on the benefits of SPC.

A lack of resources is another reason for improper metrology. Especially in these lean times some companies don't have the personnel or equipment to perform it correctly. They make due with the systems they have in place, not understanding that a small investment in metrology will pay for itself in the long run. Examples of how investment in proper capability studies and SPC can quickly pay for itself can be found below in the "Lost Revenue" section.

The last common reason metrology isn't properly conducted or invested in is usually a case of a bad prior experience . Someone thought they had set up a good SPC and capability system but they didn't see much of a reduction in the cost of poor quality. Because of this they don't see the value in spending resources to set up a system now. Often that experience that earned metrology a bad reputation included a metrology process that would not have passed a MSA. After the frustration of dealing with unreliable numbers that lead to wrong decisions, they just don't want to go through it again. Setting up a capability and SPC process only halfway or even partially incorrectly can cause more problems than it will solve.

Lost Revenue

Without proper metrology processes in place manufacturers increase their costs without even realizing it. The cost of poor quality includes costs associated with appraisal, prevention, and failure. These costs are hidden and therefore, perpetuate. Adding true metrology processes reduce a facility's cost of poor quality while boosting the company's bottom line. The following are a few real examples of companies that changed their processes and the money they saved.

The first example comes from a large OEM that runs product with restrictions on rework. If defects are found, the affected boards need to be thrown away. This adds a large cost to manufacturing when defects are high. This product was run on a line of equipment that was seven years old and had a historic DPMO (defects per million opportunities) of about 40. As part of a six sigma process improvement project the company set a target of 15 DPMO or less. To get there they improved their metrology process and calibrated their machines. This reduced DPMO to below 15 and saved the company over $25,000 per month in scrap cost on that line alone. The improved metrology process helped them maintain these gains and apply the same process to the other lines in their facility. When savings of this magnitude are projected across 5 - 10 lines, the monthly saving can be huge.

Another example comes from a large EMS company that was having problems with really low first pass yields (around 75%). The facility didn't have any metrology or SPC programs. They knew what their defects were and when the problem started but they didn't have a good idea of how to fix it. Since the majority of defects were off location and skewed it was determined that the machine calibration should be checked. When the machine was measured with an offline system it was determined that the capability numbers for the machine were running below Cpk 1.0. This statistical analysis gives a projected defect level of 56,000 DPMO, an extremely high level. The machines were calibrated using the offsets provided by the offline system and the Cpk went as high as 2.5, correlating to about 3.4 DPMO—a significant improvement from 56,000. First pass yield was checked on the next shift and it had risen to 89%. This increase in first pass yield corresponded to a $35,000 per month savings in rework and maintenance time when applied to their entire facility.

The final example is another large EMS. They were having a problem with tombstoning on 1005 [0402] components. First pass yield for these components was about 60%. To try to improve first pass yield on the ten-year old machine they adjusted CAD data and performed maintenance. Since they didn't have a way to measure the capability of the line with any external system they were relying on internal systems alone. They decided to get an external system to measure the machine's capability. Cpk was about 0.7; after calibration it rose above 1.5. The capability change corresponded with a rise in the first pass yield from 60% to 89% with zero tombstoning errors. This reduced rework and allowed them to use their original CAD data, saving engineering time and allowing their product to become more portable.

Conclusion

Capability studies and SPC are key components in running world-class facilities with a low cost of poor quality, but they require good metrology systems. Companies without real metrology can be leaving large savings on the table. In the competitive manufacturing environment, these hidden poor quality costs have to be removed to keep the company viable. Metrology done correctly can do just that. But past perceptions and lack of knowledge need to be removed as roadblocks to setting up these systems that will save a company money. Over 100 hundred years ago Lord William Thomas Kelvin stated "If you can not measure it, you can not prove it." It could have been more accurately stated "If you can not measure it correctly, you can not prove it." And if you can not prove it, you can not improve it.

[1] Wikipedia, http://en.wikipedia.org/wiki/Metrology, 2008
[2] NIST Historical Collection **http://museum.nist.gov/object.asp?ObjID=35**

Poor Metrology:
The Hidden Costs

By: Mike Cieslinski

April 2010

Does…

measurement = metrology?

No.

Introduction

- **What is metrology?**
  - Definition
- **What are Internal Calibration Systems?**
  - Definition
  - Benefits
  - Limitations
- **Benefits of Metrology**
- **Keys to good metrology**
- **Examples of lost revenue**

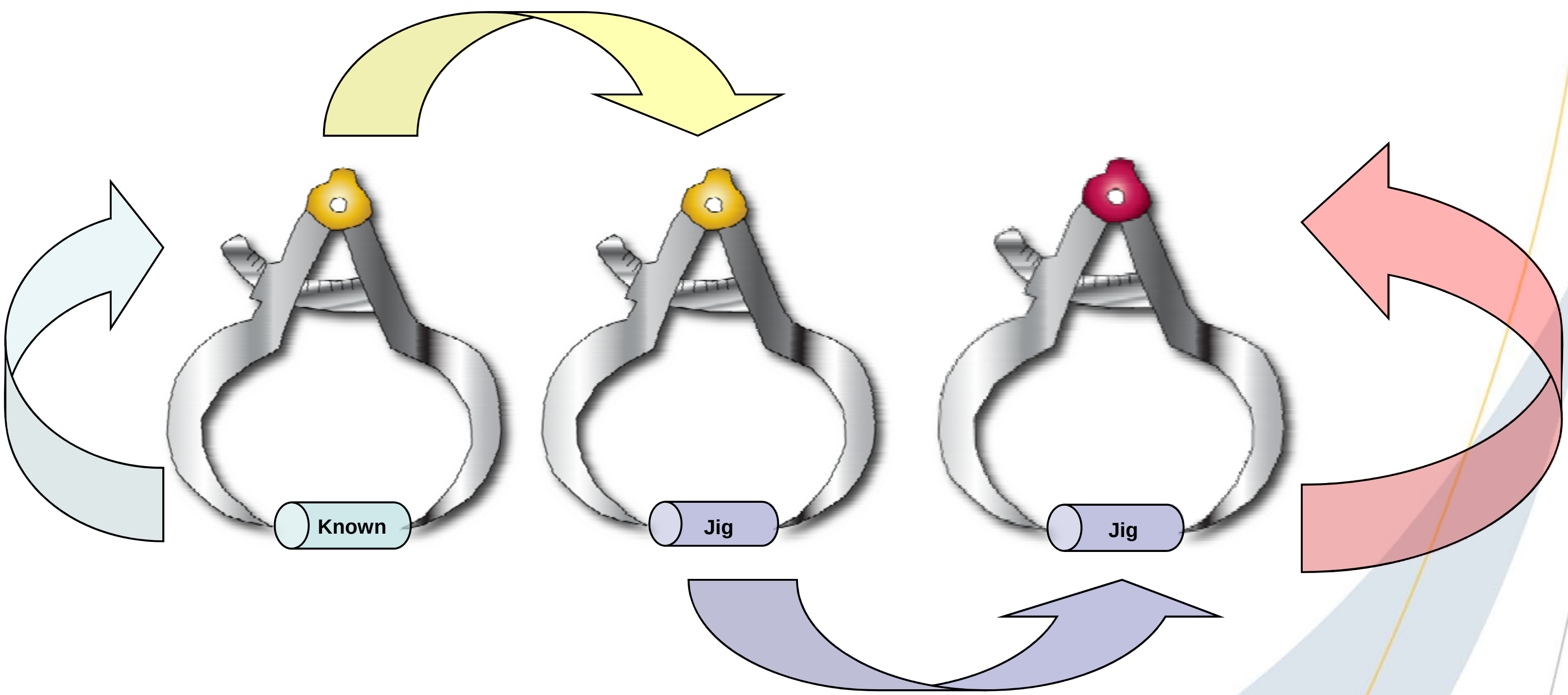
Definition of Metrology

"The property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties." *–Wikipedia*

International Bureau of Weights and Measures

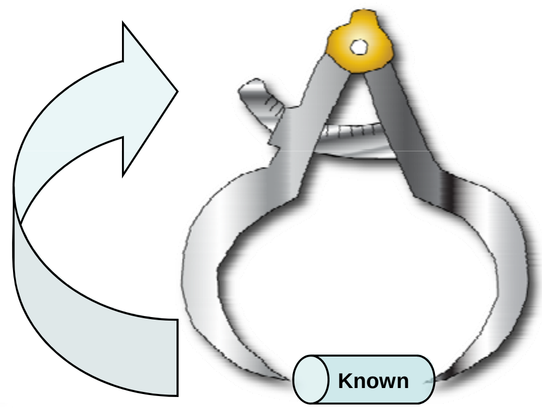
Definition of Metrology

- Traceability
  - Same measurement anywhere in the world
  - Unbroken chain of measurements
    - Known Standard
    - Inspection Device
    - Jig
    - Inspection Device
  - Uncertainties included along the way



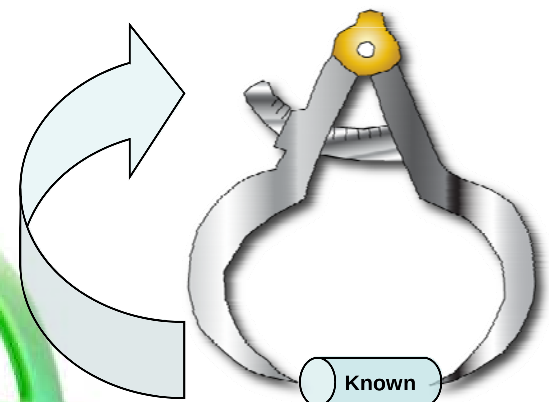
Definition of Metrology

- Uncertainties
  - All measurements have some level of uncertainty
  - Better inspection devices lower the amount of uncertainty transferred to the next measurement
  - Uncertainty comes in the form of errors
    - Repeatability
    - Reproducibility
    - Bias

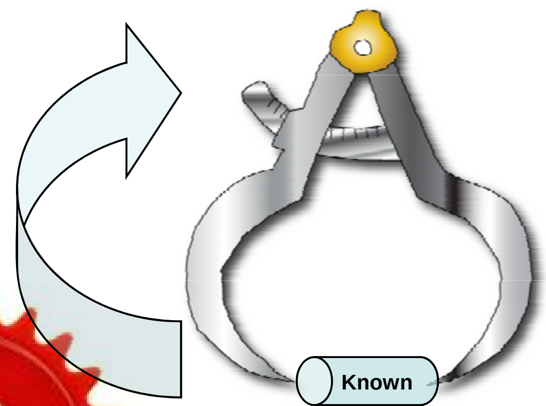


Definition of Metrology

- Repeatability of a measurement system is the short term variation of the measurement equipment.
- No variation in the environmental variables
  - Operator
  - Temperature
  - Humidity
  - Time
  - Artifacts
  - Measurands

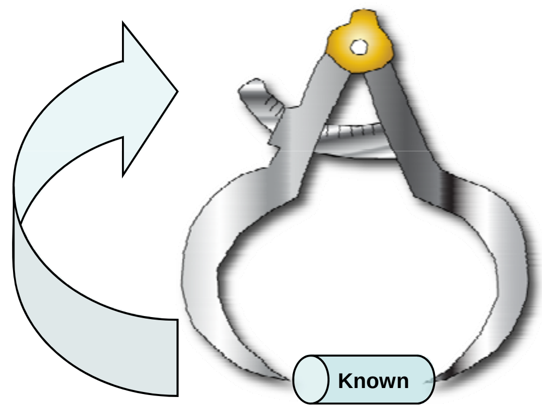


- Reproducibility looks at the long term variation of a system
- Variation when environmental variables change
  - Operator
  - Temperature
  - Humidity
  - Time
  - Artifacts
  - Measurands



Definition of Metrology

- Bias is the deviation from the known value to the measured value.
- “Known values” hold the measurement uncertainties that have been passed down



Definition of Metrology

- Total Error is the summation of all the forms of error using Sum of Squares
  - Repeatability
  - Reproducibility
  - Bias
  - Known artifact uncertainty
- The total error is compared to the process tolerance and this is called the Process to Tolerance (PT) ratio.
- PT Ratios
  - Less than 10% = excellent inspection
  - Less than 25% = acceptable inspection

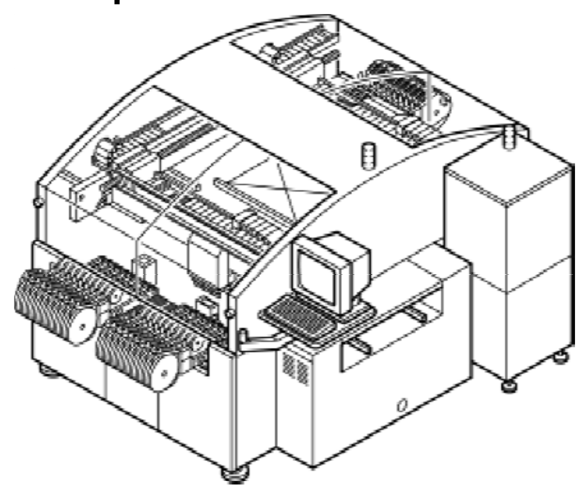
Definition of Metrology

SMT Industry Standard Implementation

- Use Coordinate Measurement Machines (CMM) to measure parts placed on boards
- The CMMs should be calibrated annually using jigs from the manufacturer of the CMM
- Users define their own algorithms using standard inspection tools to measure parts.
- Algorithm definition = large source of error & bias
- User needs to create own artifacts to measure bias or use IPC9850 standards.

Internal Calibrations

- Internal calibration systems are systems that:
  - Set offsets
  - Check machine repeatability
- Needed due to:
  - Number of offsets
    - 20 gantries including up to 68 spindles
    - Multiple cameras
    - Pickup locations
    - Rotations
  - Complexity of machines



Value of Internal Calibration

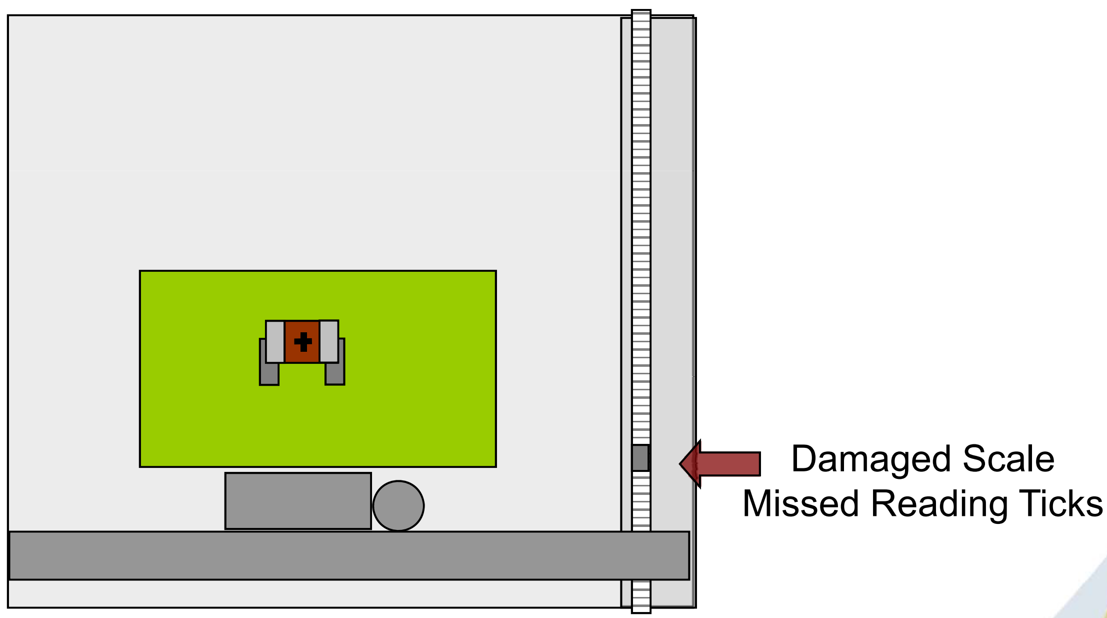
- Simplification of Service
  - Easier part replacement
  - Less maintenance staff training
- Speed
- Repeatability of Calibration
  - All operators will get the same results
- Instant Feedback
  - Provide standard deviations to show system variance

Why Internal Calibrations Don’t Qualify as Metrology

- No traceability
  - Inspection systems on machines are not calibrated with traceable jigs
  - MSA not done on machines
- PT ratios not acceptable
  - Fail discrimination
  - PT ratios not acceptable

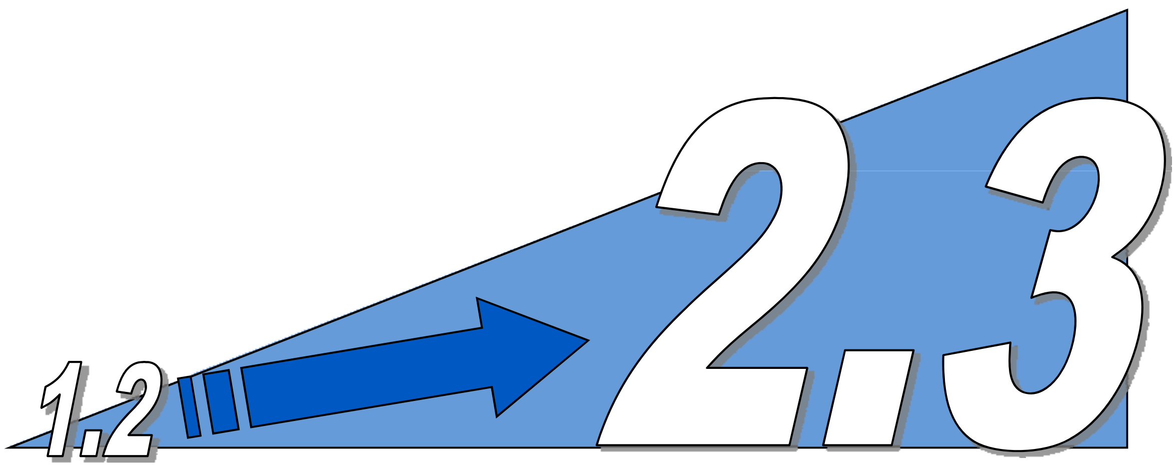
Why Internal Calibrations Don't Qualify as Metrology

- Masks internal issues
  - Same drive system measures and places
  - Repeatable errors don't get measured
  - Damaged Scale Example
    - Reports 0 Deviation



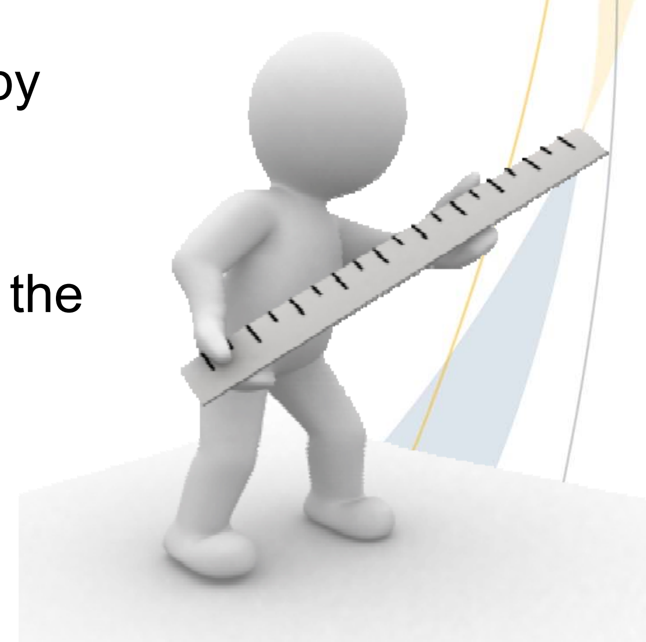
Why Internal Calibrations Don't Qualify as Metrology

- Inflates Capability Numbers
  - No way to determine Stage to Stage
  - No way to determined Machine to Machine
  - Masked errors get reported as 0



Why Internal Calibrations Don't Qualify as Metrology

- Customer Y
  - Initial State:
    - machine "X" > 2.0 Cpk on internal system
    - had problems with placement
    - thought machine was fine
  - Action Taken by Customer Y:
    - investigated CAD data and other problems but no issue found
    - solution = continue to adjust CAD data by approx. 0.2mm
  - Results of External Measurement:
    - system showed a 0.244mm deviation in the X direction bias
    - true Cpk of machine was negative



Keys to Good Metrology

- Inspection system must be validated using a Measurement System Analysis (MSA).
- MSA is a series of tests that check for the following errors:
  - Repeatability
  - Reproducibility
  - Bias
  - Gauge uncertainty
  - Discrimination

Gauge R&R Test

- Determines Repeatability, Reproducibility, discrimination; but not bias
  - Kate is most repeatable
  - Sue & Mary are reproducible
  - Which is correct?
    - Determined by bias

Measurement	Operators		
	Sue	Mary	Kate
1	4.1	4.4	3.1
2	4.5	4.5	3.2
3	4.3	4.2	3.2
4	4.1	4.7	3.2
5	4.7	4.1	3.2
6	4.8	4.3	3.3

Keys to Good Metrology

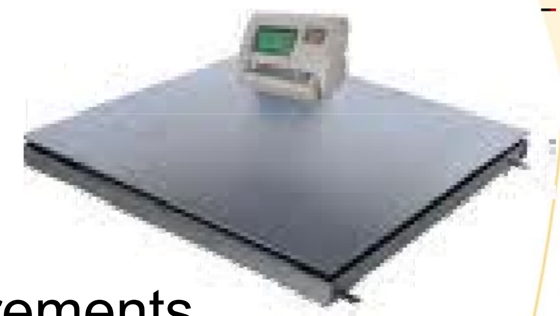
Gauge R&R Test

- **Types of tests**
  - – ANOVA
  - – Average Range AIAG version 3
- **General test design**
  - – 2-3 operators
  - – Measure 20-30 parts
  - – 2-4 times
- **How to design test**
  - – Depends on the source of error
    - If from repeatability more measurements makes sense
    - If from operators using 3 operators instead of 2 is a good idea

Keys to Good Metrology

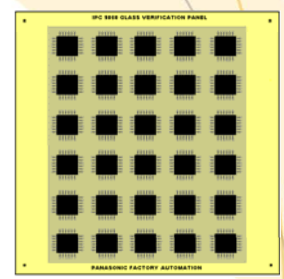
Gauge R&R Test

- **Discrimination = resolution (decimal places) reported by the inspection machine**
- **Measure of discrimination is in distinct categories**
  - 5 distinct categories is acceptable
  - 10 distinct categories is excellent



- **Resolution Example:**
  - Industrial scale measure in 100 lbs increments
  - Weigh people ranging from 75 – 249 lbs
  - Only 100 or 200 would be reported
  - Discrimination of this scale is not adequate to measure people
  - x10 rule would state that measuring in the 100's range would require a scale of 10

Keys to Good Metrology



Accuracy Test

- Purpose of test is to determine bias
- To run this test, create an artifact traceable to a National standard
  - should replicate the inspection measurement
  - should include deviations from target
- IPC9850 accuracy board fits this descriptions
- Bias = calculation of measured value → “True value”
  - defined by the traceable results from the artifact

Value of Metrology and SPC

- **As part of a Six Sigma program data from SPC can be used to:**
  - Determine special cause variation
  - Fix problems before defects are created
  - Reduce the cost of poor quality
  - Save problem debug time
  - Increase line operation

Why Metrology is Done Wrong

- Lack of knowledge
  - AOI
  - Internal calibrations
- Lack of resources
- Bad experience in the past with bad SPC system

Lost Revenue

- Problem: OEM with high defect rate
  - No rework on board allowed
  - Equipment 7 years old
  - Historic DPMO about 40
  - Six Sigma improvement goal: DPMO 15
- Solution: Implemented an improved metrology system
  - Saved $25,000 a month for 1 line
  - Began implementing metrology over other lines as well for further savings

- Problem: EMS company had low first pass yield (75%)
  - No metrology data available
  - AOI reported high numbers of misplaced and missing
- Solution: Brought in a inspection machine to check capability and calibrate their machines
  - Cpk went from <1.0 to 2.5
  - First pass yield went up to 89%
  - Saved $35,000 a month for entire factory for rework

Lost Revenue

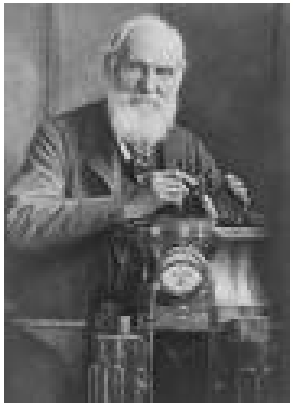
- Problem: EMS company with tombstoning 1005 [0402] components
  - First Pass Yield: 60%
  - Adjusting CAD data to compensate
  - Machines: 10 years old
- Solution: Brought in a inspection machine to check capability and calibrate their machines
  - Cpk Before = 0.7
  - Cpk After = 1.5
  - First pass yield after: 89%
  - 0 tombstone errors

Conclusion

“If you can not measure it, you can not improve it.” *-Lord Kelvin*

should have read:

“If you can not measure it **correctly**, you can not improve it.”



- Improving processes reduces cost
- Metrology performed correctly makes companies more profitable in this tough business environment

Thank you