Calibrating What We're Actually Doing

Understanding Measurement in Commerce and Industry

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Accurate measurement is critical to maintain equipment and systems performance. Yet we in manufacturing often don't measure up.

Measurement is foundational to technology and commerce. Equally important is agreement on the methods of measurement as well as what the measurements actually mean. If that seems obvious, consider this observation, by Shon Anderson, CEO of 3D printer manufacturer B9Creation:

"I have a background in mechanical engineering, and I continue to be astounded on how even technical people have a poor understanding of the importance of proper measurement. It's particularly surprising in manufacturing, where misapplication of a point of calibration has serious implications for the performance of a part."

To provide a better understanding of advancements in measurement and measurement tools and how they can make manufacturers more cost-efficient, this white paper examines:

- Metrology and the Study of Measurement
- Key measurement concepts
- General overview of analytical tools and products used for industry-specific applications

Metrology
Studying Measurement

The first forms of measurement were time, weight and length. According to the Measurement Science Conference (MSC), standards of measurement were set throughout antiquity to facilitate trade, commerce and construction, but these standards were open to interpretation and frequently adjusted by the whim of royal decree. The Egyptians, Greeks and Romans all had widely accepted, albeit flawed, measurement systems. It was only until the Industrial Revolution, with the advancement of scientific knowledge and the invention of accurate measurement instruments, that a truly standardized system was achieved. Adoption of the decimal-based metric system by France in 1795 is generally considered the founding of modern metrology.

For those who might confuse the term metrology with weather forecasting, metrology is broadly defined as the study of measurement. In fact, that's exactly literally what the combination of the Greek words "metron" and "logos" means. However, as Scott Sandwith, Custom Project Manager for New River Kinematics and 2019 Chair of the Coordinate Metrology Society (CMS), points out, "There's actually a pretty big envelope that contains what's generally called 'metrology'—from theoretical and experimental study to practical application."

Beyond the theoretical study of measurement, metrology provides a set of standards by which governments and scientific bodies can establish the traceability (a record of measurements), reliability and accuracy of materials. The U.S. Department of Commerce's National Institute of Standards and Technology (NIST)is one such agency, founded in 1901 to set standards international trading partners could agree upon.

Back at the beginning of the 20th century, measurements might concern how much oil is there in a standard oil tank or whether a product has certain percentage of ore in it. These days it's more complicated, covering everything from the amount of allowable pesticides in food products that's safe for human consumption or the percentage of water contained in grain or complex drug formulations designed to make it harder for competitors to produce generic copies.

Traceability and What to Measure

Key to any standard of measurement is to establish a record of measurements, or traceability, by which companies can ascertain if their products are in compliance. It could be the case that the agency sets standards for industry to follow, or that industry approaches the agency to help set the standards. For example, a physical laboratory calibrates a material's mass under varying conditions. A company that uses that material then has a reference point to assess whether its own measurements are correct. This ensures not only the integrity of the product, but also the accuracy of the measuring equipment.

The science of measurement is both a process of deciding that something should be measured in a certain way as well as discovery that of other factors that come into play. Test results sometimes lead to values that weren't originally anticipated.

Measurements Require Context

According to Peter Douglass, Director of Technical Operations for Protolabs, a manufacturer of custom prototypes and on-demand production parts, measurements require context. "Take the standard auto servicing duration of 3,000 miles or six months between oil changes. But that doesn't take into account the type of terrain the vehicle is travelling , or at what constant speeds or temperatures and other environmental conditions. A vehicle continually operating in rough conditions at shifting speeds in hot weather is probably going to require different maintenance than a vehicle that operates under less harsh conditions at constant speeds and regular downtime."

Promoting Tolerance

Most people think that just because something is stated to be a certain size, that everything will be that exact size. But that depends on how exact you need to be. "You have a set of wheels on your car that are supposed to be so many inches in diameter and width," Anderson says. "But if you were to measure them with a certain level of precision, you'd find out that none of the wheels measure exactly the same."

The key word here is precision. And the key for proper measurement is exactly how precise do you need to be? If you're buying a set tires, it's enough to know that they are labelled 15 inches in diameter, even if in fact at some level there is actually a variation. Here you don't need to be so precise. In other cases, being close won't be close enough.

Which brings us to the concept of tolerance, the permissible variation in a physical dimension. "A high tolerance would be something like plus or minus 100 microns," Anderson says. "Now, one point of confusion here is that we're not accustomed to the metric system, so a hundred sounds like a lot. But 100 microns is about the thickness of a strand of hair. So if you have a part that has to be +/- 100 microns, there's not a lot of room for error."

Tolerance is an important concept because if you've got, say, a 2-inch hole and a 2-inch shaft, they won't fit together because they're the same size. But it is not simply a matter of making the shaft slightly smaller that 2 inches. Because, what exactly does "slightly" measure up to? "What you do is set a tolerance that specifies if the shaft is within a certain dimensional range, that'll work to fit our 2-inch hole," Anderson explains. That range is defined not just whether the shaft fits into the hole, but how tightly it needs to fit in order to perform correctly. Obviously, a 1-inch peg will fit into a 2-inch hole, but probably in most applications that's going to be way too loose. "An important part of setting tolerance is determining how tightly the part needs to fit in order to be functional," Anderson points out.

Equally important is the measuring equipment employed. "Just because you've got a digital gauge that says it can measure to so many microns doesn't mean it can actually provide an accurate measurement. If you've got a $10 caliper from Lowes, it means it can approximate the stated accuracy, not achieve it. So, if you have to be precisely accurate to determine an exacting tolerance, you need more accurate measurement equipment."

Joining New Materials

Joining dissimilar materials to create lighter weight components is a major challenge requiring precise measurements and testing to ensure commercial commodification. Lightweight Innovations for Tomorrow (LIFT), operated by the American Lightweight Materials Manufacturing Innovation Institute, is a public-partnership funded to develop and deploy advanced lightweight materials manufacturing technologies as well as provide training in the use of these technologies. A recent project launched as part of LIFT's Fast Forge program specifically addresses the testing and prototyping of new mixed-materials.

As part of the Fast Forge project, LIFT and the Center for Automotive Research (CAR) plan to publish in October 2019 findings that recommend optimal joining techniques for specific material combinations. The objective is to provide a shared industry catalogue of materials selection criteria, computer-aided engineering results, physical testing data and application uses.

The automotive industry is particularly interested in ways to save on vehicle weight using a wider range of materials, including different types of metals and polymer composites. A lighter car results in improved fuel efficiency; it almost goes without saying that a lighter car must also be a safer car, able to withstand not only everyday driving conditions, but the possibility of impact.

Complicating this is the industry's adoption of electric and hybrid drivetrains. "Batteries are heavy and add weight that we have to take out some place else in the vehicle," Shashank Modi, Research Engineer at CAR notes. He adds that, "Autonomous and connected technology will also add electronics into a vehicle's structure that we'll have balance out."

Of course, automakers have been using lighter materials since the oil crisis of the 1970s propelled higher fuel efficiency standards coupled with environmental concerns regarding engine emissions. In fact, even the smallest vehicle today is safer than a heavy-duty truck built 20 years ago, Modi points out. You might think after all these years that by now the auto industry is reaching the point where it's getting difficult to incorporate any lighter but still structurally sound materials—in which case, you'd be wrong.

Continued Innovation

"There really is no limit in sight," notes Peter Czech, LIFT Director Government Programs. "We continue to innovate thanks to technologies that weren't available just five to ten years ago. The use of newly developed composites and joining methods not only results in lighter, more fuel-efficient vehicles, it also saves manufacturers money with better, more efficient production processes".

In testing mixed-material joining processes, the project will employ all standards developed by organizations such as ASTM, ISO, SAE, and the automakers. These standards were first implemented during the Industrial Revolution to ensure the chemical composition and quality of new materials such as steel being used in railroad tracks. Czech describes the testing process as follows:

- A desired key application is defined; e.g., a car floor pan of a specified gauge.
- The project team decides ideal mix of materials to achieve weight/performance objectives.
- The team will test and narrow down the mixed-material joining technologies by computer simulation. Then, the selected technologies will be physically tested at the "coupon level" comprising a small sample of (e.g., 2" by 5") of joined material that is subject to various pulling, pounding, glazing and corrosive analyses.
- If the coupons passes rigorous testing, a recommendation is made to manufacturers on how to proceed.

"Just because we might recommend a mixed material doesn't necessarily mean the OEM is going to go out and adopt it," Czech notes. "Our job is to provide a user-study that demonstrates what standards are achieved and the technology to use should they decide the mixed material meets their business objectives and fits their manufacturing processes. There's a lot of capital investment that goes into adopting new processes; we serve as a proving ground to justify that investment."

Data is Information
The Good and Bad of Big Data

Shanton Wilcox, Manufacturing Practice Head at Infosys Consulting points to an evolution in aftermarket products switching from selling parts to selling services. "The traditional approach is you bought a part or an assembly and you maintained and then replaced it when it wore out or broke or required an upgrade," he says. "In today's world, we're not selling parts anymore, we're selling services. The service depends on information. You purchase an asset that tells you when it needs to be serviced and generates data to determine how you run it as cost-efficiently as possible."

He adds, "There are a lot of buzzwords today about predictive analytics, and there a lot of moving pieces. I have to say that a younger workforce used to looking at data on dashboards is going to help a company determine what the data is telling it, as will evolving algorithms that automatically detect patterns. But the main thing is that a company has to look at its resources, figure out what capabilities it is willing to invest in and those it needs to contract out with others, be it data scientists or IT consultants or wherever they don't have expertise. No one has all the capabilities in-house to figure this out on their own."

Collecting all this data is perhaps one of the biggest factors contributing to the complexity of measurement is what is frequently termed as "Big Data." The sheer amount of data being generated by smart systems can be overwhelming. Metrologists seek to turn relevant data into something usable. Sandwith explains, "The objective is to provide accurate measurement of a given object to ensure it fits into a variety of systems. Essentially, we translate dimensional data into information that can be used in inspection, assembly and production activities."

Douglass points out that, "We help product developers and engineers quickly identify part design issues before they even order by providing free design for manufacturability analysis." To help accomplish this, Prototypes provides an on-line interactive e-commerce platform that significantly streamlines and speeds prototyping and end-use production.

"It's a means of discovery for a manufacturer to take an idea and test it out, see what materials are right and whether they satisfy the needs of an application," Douglass says. Such simulations are the tools of the future in attaining more precise measurements with more intricate geometries. "On-line simulations expedite and optimize testing that previously had to be done through trial and error," Douglass says. "We're reinventing manufacturing by providing an integrated software platform that can handle and interpret a lot of complex data and easily arrive at measurements that lead to more efficient, better processes and parts."

IoT and AI

Douglass notes that, “These days with the Internet of Things (IoT), we’re generating vast quantities of data. It can be sometimes difficult to sort through it all.”

“Machine learning and artificial intelligence (AI) are important tools to help us sort through this,” Otlhoff says. “A related issue is how we sort and store relevant data. We need a single reference source where companies and scientists designing materials for new markets can easily find the data they need. And contribute to that database with their own findings. Right now, information could be in various locations that if you don’t know where to look, you won’t know what data is available and what you don’t need to reinvent.”

“There’s no silver bullet,” Wilcox says. “You may be looking through two to three years of aggregated data before you’ve actually determined what your most important metrics are, and the only thing you are sure of, is that the metrics will change again.”

It can be hard to figure out where to start. Wilcox, thinks the best practice is to first have an idea of just what you want to measure and spend time focusing on the right question. “Then you aim your resources to not only figure out what data supports those analytics, but also to look for measurements you didn’t anticipate.” It may turn out that old measurements don’t actually measure up. “Preconceptions can be a danger,” he says. “If you’re only looking at what you expect, you won’t anticipate the unexpected.”

Douglass agrees, “You have to be open to going beyond your expectations and looking for data that might point you in a better direction.”

Measuring in 3D

"Everyone thinks 3D printing is a magic box that just works," Anderson says. "There are a lot of physical and optical measurements involved that have to be right. For our own production at B9Creations, we've invested in equipment worth $50,000 to make our products exactly the way they need to be for the intended applications. Someone can't really expect to pick up a $700 3D printer and expect it to make parts the way our machines can."

According to Anderson, there are really three components to a 3D printing solution—hardware, software and materials. "The hardware, the printers we make, have a level of accuracy and repeatability that's never been seen before. We think the technology is pretty solid. What needs to be optimized are the software and the materials to achieve the highest tolerances. Development of software to run specific manufacturing applications is relatively new and still developing. As for materials, certain resins, for example, have a high degree of variability because they need to contain things like UV blockers. If the materials can be made more consistently even with those additives, then you can produce parts using those resins with even higher tolerances."

Sandwith agrees, "Many existing programs aren't designed to handle the data we can give them. For example, let's say we have a tool that centers holes ever 16th of an inch. But we have a solution that can significantly improve the process if we make every other hole a third smaller of that integer. That's a potentially difficult thing to achieve if the software running the tool can't accommodate that kind of change."

"We're not looking to replace physical measurement. Different situations require different kinds of tools. 3D metrology is just another tool for the toolbox," Sandwith says. "An additional advantage of this tool is that it provides feedback. We're collecting data that can be used to further refine the process and develop better designs for the use of the tool."

Douglass notes that, . "It's a great tool for problem-solving. It allows you to make structures that have never been created before." Take for example, stainless steel. "Particularly for applications in automotive and aerospace, you want metals that are light, but have the strengths to withstand harsh environmental conditions," Douglass notes. "Simulations and 3D printing open the door to play with the metal in ways to adjust for weight and stress values until you come up with an optimal balance."

Advances in Instrumentation

Thanks to advancements with instrument technology and software integration, Sandwith observes, that the application and realizing the value delivered by the systems and users are easier to achieve. It is also becoming more common and essential in advanced manufacturing processes.

Case in point: The classic Boeing 767 and 747 aircraft were developed using physical master models and gages to control the configuration and the tools used to build the parts. "They were expensive to build and took time to maintain and store for the life of the program," Sandwith says. "In today's terms developing and maintaining physical masters and gages for an airplane program would cost billions of dollars." Today, however, 3D metrologists using $200,000 instruments are building the tools and assembling parts directly from the nominal CAD (Computer Assisted Design) models with real time feedback.

Another example is the use of a robot placed on a rail with a laser tracker and a scanner for manufacturing. "Instead of a large and fixed machine that might cost $10 million, the robot on a rail with a laser tracker is a flexible machining and assembly system that can deliver most of same applications for a tenth of the cost. These hybrid systems that combine a robot and precise metrology systems with scanning capabilities is where industry is heading today," Sandwith says.

Data is Information—Communicating the Value

While you might think industry is tripping over itself to adopt these new advancements in instruments, that's not necessarily the case. While industry is starting to ramp up adopting these Metrology Guided Automation solutions for their flexibility and value, there are several reasons they have not become standard off-the-shelf commodities, Sandwith explains.

"Metrologists as a general group are focused on solving problems and delivering value. After completing the solution, they typical move on to solve the next problem or opportunity," he says. "They are not necessarily good at communicating to end-users the value they and the metrology system delivered and how they improved the processes. One of the reasons the Precision Path Consortium was started, was to connect with industry to look at their needs to manufacture large-scale, close tolerance parts and products and how measurement technology can best address those needs."

Another issue relates to software. "Robust automation solutions require flexible simple user interfaces and they need to handle out-of-sequence steps. Automating these solutions to manage out of sequence process steps requires that the software track and visually provide feedback to users which tasks are complete and which ones still need to be done. That is particularly important when the fabrication, inspection or assembly process take multiple instrument positions or occur over different shifts. The automation software also needs to include process error trapping to ensure the setup, instruments and measurements are reliable." Sandwith notes.

Finally, Sandwith points to the problem with any disruptive technology. "You're always going to get pushback from introducing something new, particularly if people feel it alters what has been working. Again, that's where communication comes in. We want to enable the production operators to be able take advantage of the metrology without them having to become a metrologist. Instead of having to go to a measurement technician to do a benchmark test every time there is an issue, we want to give that operator the tools to do it quickly and efficiently on the spot, without necessarily requiring an understanding of the science behind it."

He believes the metrology automation solutions are continuing their expansion into both common and more complex applications. New systems are merging technologies. For example, videogrammetry and laser scanners are integrated with laser trackers and Coordinate Measuring Machines. These systems are being directly integrated into production machining systems utilizing robotics to precisely drill hole patterns used to accurately assemble parts. These advancements are accomplished with advanced software solutions to deliver data and information that is much easier to understand and help communicate results with great confidence.

**"Market forces have put a focus on certain technologies that manufacturers can adopt on a mass scale. What these manufacturers will do once they have these instruments fully integrated into their production processes is going to lead to the next stage of innovations,"
Sandwith points out.**

Metrology and Industry 4.0

Measurement has historically been the foundation of commerce and progress. The future of metrology is to provide tools and processes that provide the right measurements that lead to the right results. Industry 4.0 trends in automation and supply chain optimization require the appropriate measured responses.

Resources

B9Creations is a leading manufacturer of 3D printers and scanners, 3D printing solutions and post-processing automation products. The company's product line is engineered to give users fast, dependable and easy-to-use solutions that deliver unmatched print resolution and value for both custom design and large-scale manufacturing applications.

Center for Automotive Research (CAR) is an independent non-profit conducting research and analysis to educate, inform and advise stakeholders, policymakers and the general public on critical issues facing the automotive industry, as well as that industry's impact on the U.S. economy and society.

Coordinate Metrology Society (CMS) is comprised of users of 3D portable and stationary measurement technologies, service providers and OEM manufacturers of close-tolerance industrial coordinate measurement systems, software and peripherals. The organization offers professional certification programs, industry initiatives and an annual conference to share knowledge of advancements and applications of any measurement or software solution that produces and uses 3D coordinate data. It also offers training programs and industry initiatives such as the Precision Path Consortium for Large-Scale Manufacturing to promote the science of dimensional metrology.

Infosys Consulting works with clients to apply advanced operations capabilities to integrate and streamline value chain operations for aerospace and defense, automotive, high tech and consumer goods, among other industries.

Lightweight Innovations for Tomorrow (LIFT) is an industry-led, government funded consortium. It is dedicated to reimagine processes and procedures through a highly linked and leveraged network to facilitate technology transfer into supply chain companies and empower the lightweight metals workforce.

Protolabs is the world's fastest manufacturer of custom prototypes and on-demand production parts with manufacturing facilities in five countries. The company's technology-enabled 3D printing, CNC machining and injection molding accelerate product development, reduce costs and optimize supply chains.

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