PrecisionPath Technology Roadmap

Moving Advanced Manufacturing Forward

AUTHORS:

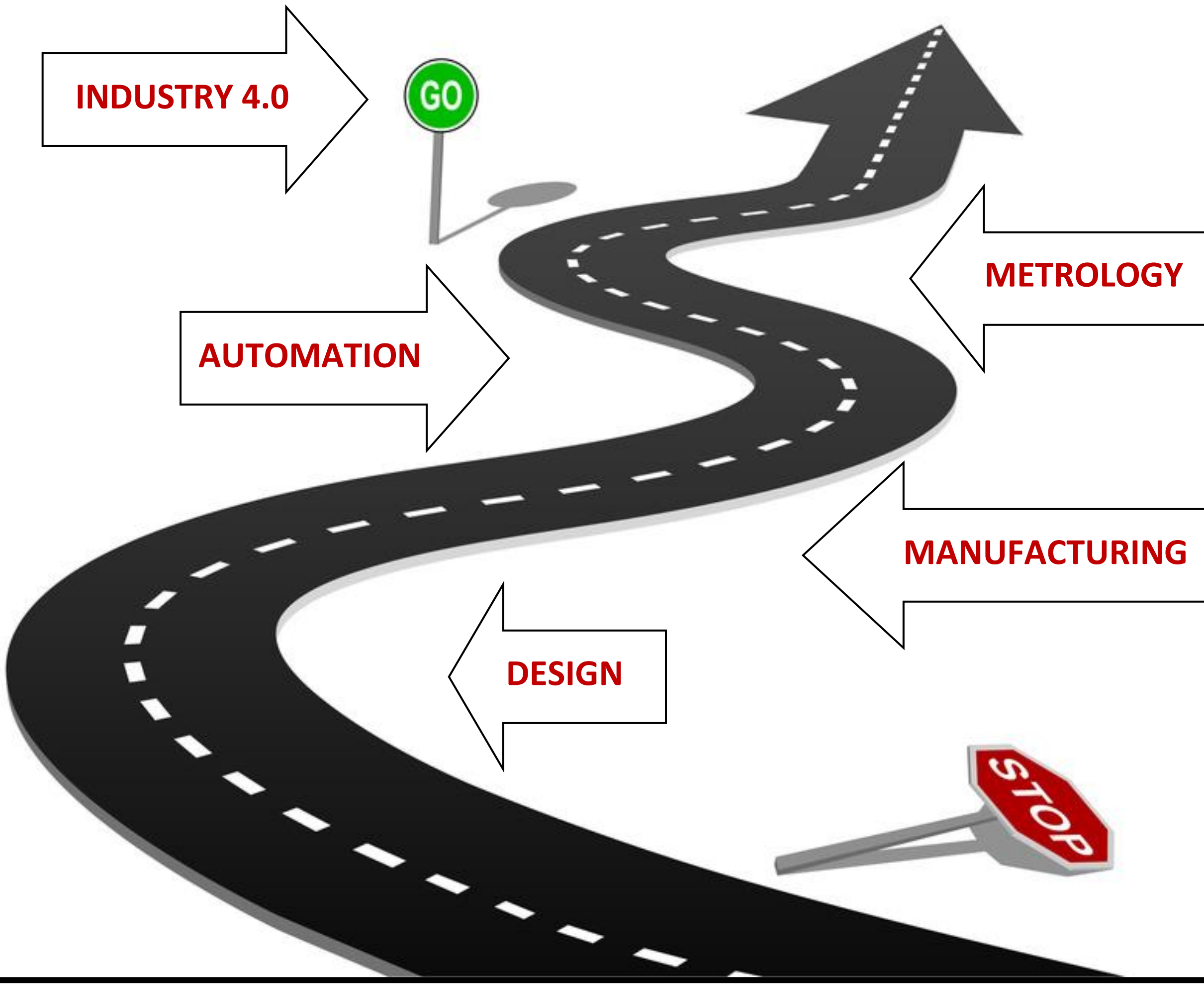
Industry Coalition

Coordinate Metrology Society

UNC Charlotte

Precision Path Consortium
for Large-Scale Manufacturing

Welcome To Our Roadmap



Industry Participation

The PrecisionPath Consortium for Large-Scale Manufacturing offered an industry-at-large survey enabling over 300 participants to contribute to the PrecisionPath Technology Roadmapping initiative. The survey was held from May to October 2016. Users and managers of portable metrology systems were encouraged to take the survey that addressed usage scenarios and issues impacting many industries, such as aerospace, automotive, defense, power generation, boatbuilding, satellite, oil and gas, and any related field that manufactures large-scale, precision parts that require in-place measurement. Many thanks to the men and women who gave us their time and consideration for this intensive survey — a vital component of the roadmap for the future!

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Executive Summary

High-precision manufacturing is a technology-intensive activity that requires specialized methods and equipment supported by a highly trained workforce. When the products being manufactured are large in scale, the challenges to achieving necessary precision become even greater.

Examples of these challenges include the difficulty in controlling the thermal state of large manufacturing equipment and the components being produced on this equipment, and the presence of gravitationally induced changes in the geometry of components. *Large-scale precision manufacturing* is practiced by numerous industrial sectors that are of critical importance to our economy and our defense security, including the aerospace, shipbuilding, energy, transportation, defense, construction and mining, and industrial equipment sectors.

The **PrecisionPath Consortium (PPC)** was formed to bring stake-holders from these sectors together with manufacturers of metrology instruments and researchers from academia and national laboratories. The Consortium's goal is to accelerate the development and adoption of technologies that will enable improved dimensional quality accompanied by dramatic reductions in production cost for large-scale, high precision components and systems.

Consortium Vision Statement

The PrecisionPath Consortium will:

- proactively engage manufacturers from a wide variety of disparate industrial sectors, along with their complete value network,
- identify cross-cutting technology challenges and opportunities,
- monitor and report on technology developments and implementation strategies,
- prioritize and communicate key research needs and directions, and
- create and continually update technology roadmaps that summarize the current state-of the art and expected future technology advances.

Precision Path Consortium

Roadmap Vision Statement

The *initial* roadmap of the consortium will explore evolution of Large-scale Precision Manufacturing utilizing Portable Dimensional Metrology, considering current and future usage scenarios, technology attributes, and other factors. This roadmap will be a living document, maintained by the consortium to support its members. Among the topics covered in the roadmap will be the following:

- Attributes of various technology "families"
- Usage scenarios independent of the specific measurement technology
- Status of cross-cutting issues such as data management
- Other issues such as workforce and documentary standards

"The roadmap will help identify initiatives of interest related to these topics and to the vision of the PrecisionPath Consortium."

Drivers for Large-Scale Manufacturing

Based on current market research, there are four major drivers in the large scale manufacturing sector. The industry is pushing forward into an evolutionary transformation of processes, efficiency, and sustainability to meet customer demand and backlogs for high precision, large products such as aircraft, automobiles, ships, windmills and more. The top industry drivers are:

1) Industry 4.0 – Automation and Big Data
2) Emerging Technologies
3) Existing/Future Projects and Market Forces
   in Aerospace, Automotive, Power Generation
4) Market Demand, Back Orders

Metrology has a greater role in this evolution, as in-place measurement is rapidly becoming forethought in the digital thread, rather than a traditional downstream process. The powerful impact of on-demand data is now being seen as an integral part of product design and manufacturing. With emphasis on empowering the production process with impactful and decision-making data, the move toward Smart Factory practices is unfolding in a variety of markets, companies and projects.

Industry 4.0 – Automation and Big Data

Industrie 4.0 (in Europe) or the Smart Factory (in the U.S.) is the leading trend in manufacturing that combines automation, data exchange, IoT and cloud computing. To give substance to this trend, a newly 2018 published update to the Worldwide Semiannual Digital Transformation Spending Guide from International Data Corporation (IDC) reveals anticipated spending on digital transformation (DX) technologies and services to be more than $1.1 trillion in 2018. This forecast translates to a gain of 16.8% over spending in 2017, with the expectation that discrete manufacturing and process manufacturing will spend more than $333 billion collectively on DX solutions in 2018. The report also expects major spending in innovation acceleration, digital supply chain optimization, applications, connectivity services, and IT services as digital transformation is pursued by manufacturers.

Germany and Industrie 4.0

Germany is very serious about their Industrie 4.0 movement, with the government investing nearly €500m (£357m) into its development.[2] The initiative started as a public-private endeavor to enhance Germany's manufacturing proficiency to compete against low cost production in China and the renaissance in U.S. manufacturing. "Manufacturing is more relevant in Germany than in other industrialized countries, like the UK," says Helmut Figalist, the head of advanced technology for the digital factory division of Siemens AG, one of Europe's biggest engineering companies. "To stay competitive in this field we need to cope with digitalization challenges." [3]

Introduced in 2011, the initiative was originally conceived by associations representing specific national interests in the country — including VDMA (machine builders), ZVEI (electronics) and BITKOM (IT) —and is now being steered by the German government. Stakeholders including heavy hitters Deutsche Telekom, SAP and Siemens hold regular meetings with government authorities. Working groups have been set up to explore issues such as standardization, research, security and the legal framework. Universities and companies pursuing an Industrie 4.0 agenda can also apply for government funding, says Figalist.

Research based on a survey of 235 German industrial companies (conducted by the market research institution TNS Emnid), PwC Consulting projects German companies will invest about €40 billion ($45 billion) annually in Industrie 4.0 efforts between now and 2020 -- about half of the entire capital expenditure they plan over this period. Productivity is set for an 18% boost thanks to industrial Internet technologies, it adds, while 85% of companies will have rolled out such technologies across all their key business divisions by 2020.[4]

Drivers for Large Scale Manufacturing (continued)

According to Alan Earls, Smart Industry Blog[5], some of the key elements discussed in the context of Industry 4.0 include:

- Ensuring interoperability. The German industry apparently has no interest in getting caught up in dueling standards, whether they are the result of differing national initiatives or competition between vendors or industry groups. So, there is a lot of focus in Germany on making sure everything plays well together.
- Decentralization. This goal implies emphasizing greater autonomy and putting intelligence at the lowest practical level. Coordination must be ensured, but a rigid, top-down organization is seen as undesirable.
- Do it in Real Time. The latest crop of technology should permit massive data collection and analysis on the fly. The focus on real time is a natural corollary of decentralization.
- Virtualization: a virtual copy of the Smart Factory which is created by linking sensor data (from monitoring physical processes) with virtual plant models and simulation models
- Modularity and Flexibility. To this self-explanatory goal should be added a desire for access to flexible services (such as software applications), all of which should enhance agility.

Three points strike at the foundation of advanced large-scale manufacturing starting with the decentralization and placing intelligence at the lowest practical level. Next, collecting, analyzing and responding to intelligent data at the production level creates a real-time closed manufacturing loop. Lastly, using 3D data acquired by sensors, digital virtualization can progress and contribute to better products, processes and factories.

The United States and the Smart Factory

Back over the pond in 2011, the United States was also making its moves to strengthen its resurgence in manufacturing. President Obama's Council of Advisors on Science and Technology (PCAST) advocated for an advanced manufacturing initiative of public-private alliances to support "academia and industry for applied research on new technologies and design methodologies." The recommendation started with $500 million per year to be appropriated to the Departments of Defense, Commerce and Energy, then increasing the investment to $1 billion per year over a period of four years.[6]

Unveiled in 2012, the National Network for Manufacturing Innovation (NNMI) was established to build a foundation to move U.S. manufacturing forward. This network of research institutes focuses on research, development and commercialization of new manufacturing technologies developed through collaborations between U.S. industry, universities, and federal government agencies.[7] Modeled after the Fraunhofer Institutes in Germany, fourteen institutes are currently in the network.[8]

In September 2016, the U.S. Secretary of Commerce Penny Pritzker announced that NNMI was rebranding under the new name "Manufacturing USA." The website Manufacturing.gov was introduced in October 2016 to serve as a national advanced manufacturing portal and information clearinghouse highlighting *Manufacturing USA* and its industry, academia and federal partners in a growing network of advanced manufacturing institutes to increase U.S. manufacturing competitiveness and promote a robust and sustainable national manufacturing R&D infrastructure.[9]

MANUFACTURING.GOV

Also in October of 2016, the Advanced Manufacturing National Program Office launched a new industry-facing website, ManufacturingUSA.com. Website visitors can learn about the continuing research, capabilities and work of each institute. The website announces the advancements and opportunities for manufacturers that are made possible by the manufacturing innovation institutes and their Manufacturing USA partners.[10]

Manufacturing℠ USA

Drivers for Large Scale Manufacturing (continued)

As related to the metrology industry, the $140 million Smart Manufacturing Innovation Institute headquartered in Los Angeles is focused on using sensors, software, data and the industrial internet to boost efficiency and reduce downtime at factories across the United States. Half of the funding comes from the Department of Energy, while the other $70 million comes from commercial participants.[11] Also, SUNY Polytechnic Institute in Albany and the University of Rochester were awarded a $600 million photonics manufacturing institute that is based in Rochester.[12] The MIT Energy Initiative (MITEI) announced it will share faculty expertise in clean energy innovation as an academic and research collaborator in the Smart Manufacturing Leadership Coalition (SMLC). This important coalition is comprised of nearly 200 partners from academia, industry, and nonprofits from more than 30 states. Their focus is to drive advances in smart sensors and digital process controls that will ultimately improve the efficiency of U.S. advanced manufacturing. [13]

GE's Brilliant Factory

Smart manufacturing technology is already being used by major companies like General Electric Company, which has dubbed their concept the Brilliant Factory. The company hosts a "Minds and Machines" conference each year to spell out their plan to help industrial operations to "get on the path to digital transformation." In June 2017, GE unveiled new advanced applications for industrial assets, environments and operations at their Minds + Machines Europe conference. According to their news release, the event outlined the path to greater productivity for customers who take advantage of advances in the company's leading Asset Performance Management (APM) and ServiceMax industrial applications, powered by Predix, GE's platform for the Industrial Internet.

With the large scale manufacturing industry fixated with productivity, cost and downtime, GE's technology vision for asset-intensive industries is to convert their operations to a predictive model instead of a reactive, break/fix service model. The company claims their solutions and deployments are scalable for both large and small companies. [14] The implications of this model are better decision-making and design, troubleshooting quality upstream vs. downstream, and of course optimized process control. The company released a downloadable white paper: *Five Steps to Digital Industrial Transformation, Your Guide to Industrial. The paper covers* digital transformation paths taken by Pitney-Bowes, Qantas Group, GE Transportation, and GE Power.

Emerging Technologies

There is an interesting tug 'o war in regards to the top emerging technologies for manufacturers in 2018 and into the future. The most common themes form around the fact that manufacturing is going digital, becoming decentralized and breaking free from economies of scale.

According to Gartner's Top Trends in the Gartner Hype Cycle for Emerging Technologies 2017, there are three megatrends pushing the industry forward: artificial intelligence (AI), transparently immersive experiences and digital platforms. The IT research and advisory company urges technology innovation leaders to explore and ideate these three mega-trends to understand their future impacts. "Interconnected ecosystems" is the key phrase here, as smart machine technologies and software are revolutionizing manufacturing and its related industries. [15]

Another source of research was captured in The World Economic Forum's white paper (available for download) prepared for the manufacturing community in 2017. A panel of experts draw on the collective expertise of the Forum's communities to identify the top technological trends. This white paper was released in the context of the Forum's Initiative on Shaping the Future of Production that was launched in 2016. The research points out that there are 60 technologies and philosophies in the current landscape that impact production systems. The keys to transformation require management and government leaders to ready their workforces, prepare their infrastructures and supply chain in order to leverage the benefits.

Drivers for Large Scale Manufacturing (continued)

The organization cites 5 disruptive technologies in various stages of technical readiness and adoption with powerful potential to shape the future of manufacturing:

1. Advanced Robotics - $35B market
2. 3D Printing - $5B market
3. Artificial Intelligence (AI) – 272.5M market
4. Enterprise Wearables - $700M market
5. Internet of Things - $105B (manufacturing only – IDC Worldwide Semiannual IoT Spending Guide) [16]

Some of these technologies are closer to fruition than others. As per the report, robotics and 3D printing have longevity in the industry and are on the cusp of mainstream adoption. Artificial intelligence and enterprise wearables are considered to in the embryonic stage. North America, Europe and pockets of Asia (China, Japan and South Korea) are leading in technological adoption. [17]

Other impactful transforming technologies are distributed manufacturing, predictive analytics and the Smart Factory. The distributed manufacturing concept is to replace physical materials in the supply chain with digital information, according to the Meta-Council on Emerging Technologies at the 2015 World Economic Forum. [18] Mark Bünger, a research director at Lux Research, states the revolution comes from emerging tools and technologies, such as 3-D printing, that can manufacture one part as cheaply as many parts. As a result, manufacturing is able to become decentralized and independent of economies of scale.

Not every product can be made this way, said Bünger, and the manufacturing method will likely depend on the size of the demand. Distributed manufacturing enables customized products to be created for niche markets. And because specialized products made in relatively smaller numbers can be sold at a higher price, there's a good chance of breaking even. "In some cases, distributed manufacturing won't replace an existing product, but in some cases it will completely obliterate the market," he said. [19]

In order for IoT to thrive, predictive analytics has also garnered some major ink when applied to the manufacturing industry. The push for insight-driven operations is pushing the rapid development of new, advanced software and sensors. As data is gathered at all points of production, manufacturers can analyze the information and get a better handle on every facet of their business from design to production, inventory to quality. Predictive maintenance has also advanced in the last few years, as new machines have the ability predict when they are going to fail, enabling manufacturers to optimize their maintenance schedules with historical intelligence. [20]

As manufacturers continue to experiment with Smart Factory concepts, significant progress is being made in the industrial sectors of aerospace and defense, automotive and transportation. A report has been released by Capgemini's Digital Transformation Institute (DTI) in collaboration with Digital Manufacturing Services to produce this study. Based on a survey with 1,000 senior executives planning or implementing smart factories globally, the study is entitled *Smart Factories: How can manufacturers realize the potential of digital industrial revolution*. More manufacturers are starting to create their Smart Factory infrastructure as a by-product of emerging technologies in software and sensors. The Smart Factory platform captures data and seamlessly moves it across all seams of manufacturing, exchanging and implementing information to drive improvements in productivity, quality, customer services and sustainability.

According to the DTI report, 76% of manufacturers either have an ongoing smart factory initiative (43%) or are working on defining one (33%), with 14% of companies satisfied with their level of accomplishment. North America leads adoption, as 54% of U.S. manufacturers have ongoing smart factory initiative in place today. The U.S. is followed by Germany (46%), France (44%), the United Kingdom (43%) and Sweden (39%). [21]

Drivers for Large Scale Manufacturing (continued)

Present/Future Projects and Market Forces in Aerospace, Automotive, Power Generation

The industry press has been flush with news in regard to production of new products, market changes, new factories, as well as future large scale manufacturing projects with clearly defined initiatives. These projects are driving new approaches to design, manufacturing, alignment, and assembly through the use of sensors, robotics, software and data acquisition tools.

Embraer and Boeing

The Boeing Company has been marketing its Design for Environment strategy to account for environmental performance at every step of a product's life cycle — from materials, design and manufacturing, through in-service use and end-of-service recycling and disposal. In July 2016, Boeing and Embraer unveiled another phase of the Boeing ecoDemonstrator program to test technologies to improve airplane environmental performance and accelerate their introduction into the marketplace. An Embraer E170 served as the flying testbed for advanced environmental technologies slated for operational testing in Brazil. These flights also tested several technologies designed to reduce carbon emissions, fuel use and noise including LIDAR, ice phobic paint, a new wing design, special sensors and air visualization techniques near the wing surface, and biofuel.

The 2018 ecoDemonstrator, in its fifth iteration, is a FedEx-owned 777 freighter. Its flight-test program began in March and April 2018 to gather data on 35 technologies including using 100 percent biofuel for efficient burn and reduce emissions. Studies show sustainably produced aviation biofuel emits 50 to 80 percent lower carbon emissions through its life cycle than fossil jet fuel. Boeing and Embraer opened a joint biofuel research center in São José dos Campos to perform research and coordinate research with Brazilian universities and other institutions. [22]

Boeing's 737MAX


Photo Credit: The Boeing Company

Dallas-based Southwest Airlines took delivery of its first Boeing 737MAX on Tuesday, August 29, 2017. The airline has placed an order of 200 various 737 airplanes (MAX 7 and 8) with the aircraft manufacturer. Malindo Airways in Malaysia took the launch delivery of the first MAX in May 2017, followed by the first European MAX customer Norwegian Airlines. The long awaited, fourth-generation 737Max has broken sales records and captured over 3,800 orders, adding to Boeing's backlog. According to Boeing's current FACT SHEET, it maintains the 737 MAX has an 8% lower operating cost than its main competitor. The narrow-body jetliner is designed to offer a quieter (40% less than other 737s), more comfortable ride with amenities like boarding music and mood lighting. Customers can use their own device to connect to the MAX's Wi-Fi and stream live TV. The plane's fuel economy is another big leap for the new 737 variant as it is projected to reduce fuel burn by up to 14% with its efficient LEAP-1B engines. [23]

On schedule for certification and entry into service in the third quarter of 2017, company executives stated the aircraft executed a flawless flight-test campaign, fulfilling Boeing's "Right at First Flight" mantra. In July 2017, Reuters reported that Boeing posted second-quarter profit and cash results that beat estimates and increased its full year forecasts. The company has made big investments in its 777X wing factory and the 737 MAX and 787-10 programs.[24] In March 2018, the latest 737 MAX 7 jetliner wrapped up its first test flight. This new version boasts of having the longest range of the MAX plane series, up to 3,850 nautical miles.

Drivers for Large Scale Manufacturing (continued)

Lockheed Martin

Lockheed Martin is all about the "digital tapestry" linking all stages of a product's life cycle. This seamless digital thread weaves its way through conceptualization, design, verification, manufacturing and sustainment, and gathers intelligence to better understand, troubleshoot and improve products and ideas. Their marketing focuses on additive manufacturing leading to the creation of affordable parts that are more capable and durable. The company is embracing additive manufacturing technologies to build affordable components, and integrating next-generation electronics that are reducing the size, weight, power and cost of their products and systems. Lockheed Martin's research and development efforts are also focused on advanced materials to be used in novel ways.

Lockheed Martin's digital DNA program reveals a move toward in-process inspection through the use sensors and metrology in the Quality segment. The company is also investing heavily in the field of robotics to take on numerous challenges – from disaster response to deep space exploration. More can be found about how the digital process works for them here — the Digital Tapestry.

In March 2016, Lockheed Martin announced that it is developing a Mach 6 aircraft that would be faster than any other fighter jet. The new Hypersonic Test Vehicle 3X, or HTV-3X, could reach speeds of more than six times the typical cruising speed of the Boeing 747-8, which was chosen as the next presidential aircraft. It will also far outpace anything flown by global adversaries. The HTV-3X would be three times faster than the F-22 Raptor fighter jets, flying at 4,600 miles per hour. The aircraft could travel the distance of the Earth's circumference in about five and half hours, roughly an East Coast to West Coast flight in a 747.

Lockheed Martin Chief Executive Officer Marilyn Hewson has revealed that significant progress has been made regarding the new fighter jet. "We accomplished several breakthroughs on HTV-3X. And we're now producing a controllable, low-drag, aerodynamic configuration capable of stable operation from take-off, to sub-sonic, trans-sonic, super-sonic, and hypersonic to Mach 6, "she said in a statement. And most importantly, we're proving a hypersonic aircraft can be produced at an affordable price. We estimate it will cost less than $1 billion dollars to develop, build, and fly a demonstrator aircraft the size of an F-22," she added.

Lockheed's legendary Skunk Works is working on other secret hypersonic aircraft including the Falcon HTV-2. The unmanned, developmental aircraft would be launched on a rocket and could achieve Mach 20 speeds (13,000 miles per hour) making the trip from NYC to LA in less than 12 minutes. This aircraft would fulfill the Department of Defense's objective to achieve Prompt Global Strike (PGS) — conducting airstrikes against any target, anywhere in the world within one hour. [25]

In early 2018, the company announced the launch of its 'Open Space' Satellite Innovation Project, and publicly released specifications for its satellite platforms for collaboration opportunities with companies looking to send innovative technologies to space. Lockheed Martin has produced more than 800 satellites and published technical aspects of three of its satellite platforms – LM 2100, LM 400, and the new LM 50 nanoset series. The effort is meant to invigorate a new generation of researchers, start-ups or established companies wanting to send innovative technologies into space.

"Our goal with Lockheed Martin Open Space is twofold: first, to help more companies and innovators do amazing things in space, and second, to create new avenues for collaboration so we can move faster to tackle our customers' most pressing challenges," said Rick Ambrose, executive vice president of Lockheed Martin Space. "We're not just offering launch slots, we're ready to help new companies integrate their groundbreaking technologies with powerful satellite platforms. We believe there's significant untapped potential out there waiting to be unleashed."

Drivers for Large Scale Manufacturing (continued)

The Air Force – Changing Plans

In May 2017, the Air Force released its fiscal 2018 budget with a 26% increase over 2017. The service is seeking additional funding for research and development of next-gen technologies including a sixth generation fighter and a nuclear cruise missile. Some of the funding would be applied toward acquisitions of the KC-46A Pegasus tanker, F-35A Lightning II and B-21 Long Range Strike Bomber. [26]

In 2016, the U.S. Air Force released an unclassified version of its Air Superiority 2030 Flight Plan (PDF) to rule the skies for the next 15 years. The plan revealed that the Air Force is NOT planning for the development of a new major fighter aircraft. The report states that advanced air and surface threats are spreading to other countries around the world, meaning rapidly-improving Russian and Chinese air defenses are becoming more of a threat. The Air Force plan, in short, is looking for agility to combat these advances and a "family of capabilities" approach that included a variety of technologies being put to use such as electronic jammers to blind aircraft sensors and new B-21 stealth bombers that can target and destroy enemy aircraft on the ground.

In lieu of a new fighter jet, it looks as though a new Penetrating Counterair System (PCA) will offer a different approach to deep penetration strikes. The program may consist of a stealth drone, flying under the radar gathering critical information, working in tandem with a bomber packing long-range missiles. Clearly the benefit of an unmanned PCA is that missions can be executed without risk to pilots on the front line. The Pentagon's Rapid Capabilities Office, a high security research-and-development organization has started work on an arsenal plane to supplement the F-35. [27] [28]

The U.S. Air Force has requested an additional $147M to fund the early development of the PCA. Boeing has already introduced a concept art for the PCA business. Also, the United States, United Kingdom, Germany and Japan are all in early planning stages for a so-called "sixth generation" of fighter jets. The jets won't fly until the 2030s, but governments around the world are already exploring designs.

As of August 2, 2017, the Air Force finally declared the $150M F-35 fighter combat ready. "The declaration of initial operational capability marks an important milestone as the Air Force will operate the largest F-35 fleet in the world with more than 1,700 aircraft," the F-35 program's executive officer, Lt. Gen. Chris Bogdan, said in a statement. In addition, both the UK and Japan are purchasing the aircraft. Riddled by problems and overruns, this is a significant milestone for the $400 billion program. The designation marks a major milestone for the $400 billion program. [29]

In a nutshell, the Air Force's new aircraft are late and over-budget due to long development time and other delays render the product nearly obsolete before you even take it out of the package. The strategy document recommends that the Air Force reject next-gen platforms and separate airplane-development from the invention of new electronics. This approach would enable the military to develop new weapons, sensors, and communications technologies quickly just like consumer products, to plug and play into a basic airframe developed at a slower pace.

Wind Power Industry

In April 2018, the American Wind Energy Association (AWEA) released the *U.S. Wind Industry First Quarter 2018 Market Report 2018* report stating the U.S. wind power workforce installed 406 megawatts (MW) during the first quarter of 2018. The total U.S. installed wind power capacity is now 89,379 MW with more than 54,000 wind turbines operating in 41 states plus Guam and Puerto Rico. This constitutes a 40% year-over-year increase and the highest level since AWEA began tracking both categories in 2016. GE Renewable Energy and Vestas lead with 99% of the U.S. wind turbine market. Power purchase agreements (PPA) totaling 3,560 MW were signed during the first quarter, the strongest quarter for PPA announcements since AWEA began tracking PPA activity in 2013. [30]

Drivers for Large Scale Manufacturing (continued)

In the first quarter of 2017, the industry installed 908 utility-scale turbines, totaling 2,000 megawatts (MW) of capacity. The U.S. wind manufacturing sector consists of more than 500 manufacturing facilities spread across 43 states producing the more than 8,000 components that comprise a typical wind turbine. According to the AWEA, 2017 was the industry's strongest start since 2009.

"We switched on more megawatts in the first quarter than in the first three quarters of last year combined," said Tom Kiernan, CEO of AWEA, in releasing the *U.S. Wind Industry First Quarter 2017 Market Report*. "Each new modern wind turbine supports 44 years of full-time employment over its lifespan, so the turbines we installed in just these three months represent nearly 40,000 job years for American workers."

According to the 2017 report, the early burst of activity reflected how 500 factories in America's wind power supply chain and over 100,000 wind workers are putting stable, multi-year federal policy to work. The industry is currently in year 4 of a 5-year phase-down of the Production Tax Credit.

Bloomberg New Energy Finance also released a study in March 2018 that revealed a dramatic 18% improvement in the competitiveness of onshore wind and solar over the past year. Most interesting was their projection that in most places, both wind and solar will work cheaper than coal by 2023. The Danish company Vestas received top spot in the BNEF annual ranking of wind turbine manufacturers. Four manufacturers in this industry comprise 53% of the wind turbines deployed — Denmark's Vestas, Spain's Siemens Gamesa, China's Goldwind and General Electric of the United States. Other wind power players on the top ten list are Enercon, Nordex group, Senvion, United Power, Suzlon, and Envision. [31]

General Electric

In May 2018, GE reported it has installed 40GW of onshore wind capacity in North America sufficient to power 11 million homes in the United States. There are currently more than 25,000 wind turbines running in this region. [32] GE reported that it had reached a milestone with 60,000 MW of wind installations worldwide at the end of 2017. The company's best-selling 2MW product platform has greatly contributed to the major milestone with over 2,300 turbines in operation. Another 500 MW of this platform are at various stages of development in North America.

Another landmark product launch occurred in September 2017, as GE Renewable Energy rolled out its largest onshore wind turbine. In a news release, GE reported the new 4.8MW wind turbine, GE's first onshore entry in the 4MW space, is equipped with a 158 meter rotor and a range of tip heights up to 240 meters. The combination of a larger rotor and tall towers enables the turbine to take advantage of higher wind speeds and produce more energy. The new turbine offers high tech 77-meter-long carbon blades, improved loads and controls, and taller, more cost-effective towers. New innovations GE's close partnerships with LM Wind Power, Blade Dynamics and GE's Global Research Center resulted in these new innovations. [33]

Automotive Market

Automobile sales are slightly down in the first half of 2018 in the U.S. market, as the entire industry is projected to fall just below 17 million units this year. [34] Auto sales were also down in 2017 coming in at 17.25 units, as compared to the record highs of 17.5 million in 2016, and 17.6 million in 2015. The downturn has been compounded by a glut of new and used cars in the marketplace. Industry experts are confirming the industry is experiencing a decline, but one that is manageable for the economy. [35]

Six Southeastern states now produce roughly a third of the U.S. annual production of automobiles. But there is competition in the neighborhood, as Mexico continues to win business from the big automakers. Nissan completed a $2 billion plant expansion in Mexico in late 2013. In September 2015, Nissan and Daimler broke ground for a

Drivers for Large Scale Manufacturing (continued)

$1.4 billion plant in Mexico's Aguascalientes state to make the new Infiniti QX50, and production began in 2017. In the same plant, Mercedes will produce its new A Class compact sedan to be released later in 2018. South Korea's Kia Motors Corporation opened its second North American plant near Monterrey, Mexico in May 2016. In September 2016, Audi opened a new plant in San Jose Chiapa, Mexico where it will produce the Audi Q5 SUV for a global market.

In the United States, Tesla consistently remains in the spotlight as it broke ground on 3 new factories in 2017. The first Tesla gigafactory is being built in phases, currently 30% complete. Elon Musk has projected that Tesla could have as many as 20 gigafactories worldwide. Battery cell production began at the factory in 2017, but 2018 is meant to be the year when production ramps up for their Model 3 EV. In a popular YouTube interview with Leonardo Dicaprio, Musk stated that 100 gigafactories would be needed to produce enough batteries to move the entire world to sustainable energy. Tesla has its sights set on roughly 10 -20% of that market. [36]

Tesla missed its production goals for the Model 3 by wide margins in 2017. The company is still focused on ramping up production to 5,000 units per week in 2018. Tesla reported on July 2, 2018 that 5,031 Model 3s were produced over the previous week, the first time the manufacturer had surpassed the 5,000 milestone. In a statement, as reported by *The Wall Street Journal*, Tesla maintains, "It is important to emphasize that there are no fundamental issues with the Model 3 production supply chain. We understand what needs to be fixed, and we are confident of addressing the manufacturing bottleneck issues in the near term."

General Motors reported in late 2017 that it would be pushing out two new electric models in addition to their existing Bolt and Volt, with the possibility of 18 new electric vehicles by 2023. Industry experts tout the GM announcement as significant, a turn in the road toward EVs as the future. The company sold a blockbusting 10 million cars in 2016 and is one of the largest automotive manufacturers in the world. In the past few months, a large crowd of automakers are moving in the same direction are Volvo, Aston Martin, and Jaguar Land Rover.[38]

According to Bloomberg NEF's Electric Vehicle Outlook 2018, "Our latest forecast shows sales of electric vehicles (EVs) increasing from a record 1.1 million worldwide in 2017, to 11 million in 2025 and then surging to 30 million in 2030 as they become cheaper to make than internal combustion engine (ICE) cars. China will lead this transition, with sales there accounting for almost 50% of the global EV market in 2025." An excerpt of the research can be viewed in a free public report. [39]

Market Demand, Back Orders

In recent years, the aerospace industry has experienced a renaissance, with burgeoning back orders as far as the eye can see. Boeing Commercial Airplanes employs more than 141,322 people worldwide, while other aerospace manufacturers drive the employment number up to 1 million globally. Drivers for the industry have been high oil prices until 2008 and growing markets in Asia, India and the Middle East. Boeing has projected an estimated 29,000 aircraft with a market value of $3.2 trillion will need to be manufactured in the next 20 years.

Last year, Michael Guckes (Senior Economist at *Gardner Intelligence)* reported that backlog orders across the aerospace industry were robust with the combined backlogs of Airbus and Boeing exceeding 12,000 aircraft valued at more than $2 trillion dollars. The backlog was split evenly between the two rivals. Guckes surmises it would take more than 8 years to clear the total backlog using recent annual delivery data from both firms. He also reports "GBI expects the aircraft components industry will experience continued growth as low operating costs and a growing worldwide population of air-travelers powers the expansion of the worldwide aviation market." [40]

Airline demand for bigger single-aisle jets has risen significantly. The popular Airbus A321neo has been outselling smaller Boeing's Max 9 by a whopping five to one margin. In response, Boeing rolled out its 737 Max 10 at the 2017

Drivers for Large Scale Manufacturing (continued)

Paris Airshow. This larger version of the 737 has room for 230 seats and takes a significant step toward closing the competition gap for Boeing. According to an article in CNN Money, Boeing also announced it has received 240 orders for the aircraft valued at $30 billion.

"Airlines wanted a larger, better option in the large single-aisle segment with the operating advantages of the 737 MAX family," Boeing Commercial Airplanes President and CEO Kevin McAllister said in a statement.[41]

Taking orders is easy; delivering the goods is the hard part. Fortune's Clay Dillow reported that "the industry is producing roughly double the planes it did a decade ago." Boeing produced 762 commercial airplanes in 2015, while Airbus had 635 deliveries.[42] Boeing went all out in 2016 with its production of 748 jetliners, with its output again beating Airbus' 688 deliveries.[43]

But 2017 was a game changer for Boeing. The manufacturer built more jets than Airbus last year, and won orders with a higher value. While Airbus actually delivered more jets than ever before, Boeing outpaced its rival as it scored major orders for its large and expensive widebody jets, totaling $63B for the year.[44] According to Boeing, the company delivered 763 aircraft in 2017 – more commercial airplanes than any manufacturer for the sixth consecutive year. This trend was driven by output of 737 and 787 jets, raising production on its 737 program to 47 airplanes a month. This number included 74 of its new 737 MAX. Boeing continued building 787 Dreamliners at the highest production rate for a twin-aisle jet, leading to 136 deliveries for the year.

The company grew its backlog with 71 customers placing 912 net orders valued at $134.8 billion. The total extends Boeing’s backlog to a record 5,864 airplanes at the end of 2017, equal to about seven years of production.

Lockheed Martin also reported net sales of $51B in 2017, with a backlog of $100B at the end of last year. Increased production of the Lockheed Martin F-35 Lightning II Joint Strike Fighter played a particularly strong role, with the company delivering 66 aircraft in 2017: a 40% increase on the previous year.

Automotive Backlogs

In the automotive industry, Tesla is leading the way in terms of back orders. Back in early April 2016, Autoweek reported *Tesla* was swamped with 276,000 Model 3 orders in 3 days. CEO Elon Musk admitted the company had underestimated demand for their entry-level sedan with EV fans plopping down $1,000 to reserve Tesla's latest and most affordable model. With a starting price at $35,000 before state and federal credits, and based on Musk's estimate of a $42,000 average transaction price with a few popular options, that number of reservations roughly equate to an $11.6 billion backlog.[45]

The number of reservations peaked at 518,000. As news broke that the timeline for the car's delivery has stretched into 2018, the company experienced 63,000 cancelations. However, in August 2017, Business Insider reported that the total orders for the electric Model 3 sedan is net 455,000 even after the cancellations. This pushes the backlog total to $19.1 billion. For its part, Tesla has said that it will spend about $2.25 billion on capital expenditures to get the first Model 3s to customers.[46]

Another automobile with a backlog is Toyota's hydrogen fuel cell electric vehicle, the Mirai. In 2015, Automotive News reported the demand for this new era car was pushing 2,000 units, after the Mirai went on sale in Japan in December 2014. The backlog at the time was pushing two years for delivery, and the futuristic hydrogen-powered vehicle had not even been introduced in Europe or the United States. The company has stated a very ambitious goal of selling 30,000 units a year by about 2020. This effort would constitute a major ramp up from its 3,000 unit production goal for 2017.[47]

Drivers for Large Scale Manufacturing (continued)

In February 2017, Toyota announced it had sold about 2,840 Mirai cars in Japan, the United States and some markets in Europe, as well as the United Arab Emirates. In April 2017, Automotive News reported that Toyota began promotion in China to gauge how receptive the market would be to the technology. [50] The low-volume production of key components and the limited availability of the low carbon vehicle and hydrogen stations continue to make the Mirai a niche vehicle, but Toyota continues to focus on expanding its hydrogen fuel cell concept, scaling up for semi trucks in 2017. The verdict is still out on the future of FCEV's in the U.S., as hydrogen infrastructure has grown, but it is not nearly as widespread as gas fueling and electric charging stations. California has built over 30 fueling stations, and the New England-New York region is projected to be the next area for growth. But demand for more fueling stations obviously depends on FCEV sales. [48]

Institute for Supply Management (ISM) ® June 2018 Data for Manufacturing

On June 2018, the ISM released a press release stating that economic activity in the **manufacturing sector** expanded in June 2018, and the **overall economy** grew for the 110th consecutive month, as per the nation's supply executives in the latest **Manufacturing ISM®** *Report On Business®*. The headline states the PMI® is at 60.2%. Overall, the ISM reports that new orders, production, backlog of orders and employment continue growing; supplier deliveries are slowing at a faster rate, raw materials inventories are growing, customers' inventories are too low; and prices are increasing at a slower rate; and exports and imports are growing.

The report was issued by Timothy R. Fiore, CPSM, C.P.M., Chair of the Institute for Supply Management® (ISM®) Manufacturing Business Survey Committee: The report was issued today by Timothy R. Fiore, CPSM, C.P.M., Chair of the Institute for Supply Management® (ISM®) Manufacturing Business Survey Committee: “The June PMI® registered 60.2 percent, an increase of 1.5 percentage points from the May reading of 58.7 percent. The New Orders Index registered 63.5 percent, a decrease of 0.2 percentage point from the May reading of 63.7 percent. The Production Index registered 62.3 percent, a 0.8 percentage point increase compared to the May reading of 61.5 percent. The Employment Index registered 56 percent, a decrease of 0.3 percentage point from the May reading of 56.3 percent. The Supplier Deliveries Index registered 68.2 percent, a 6.2 percentage point increase from the May reading of 62 percent. The Inventories Index registered 50.8 percent, an increase of 0.6 percentage point from the May reading of 50.2 percent. The Prices Index registered 76.8 percent in June, a 2.7 percentage point decrease from the May reading of 79.5 percent, indicating higher raw materials prices for the 28th consecutive month.

“Comments from the panel reflect continued expanding business strength. Demand remains strong, with the New Orders Index at 60 percent or above for the 14th straight month, and the Customers’ Inventories Index remaining low. The Backlog of Orders Index continued to expand, reading at 60 percent of higher for the third consecutive month. Consumption, described as production and employment, continues to expand in spite of labor, skill and material shortages. Inputs, expressed as supplier deliveries, inventories and imports, had expansion increases, due primarily to negative supply chain issues. Lead-time extensions, steel and aluminum disruptions, supplier labor issues, and transportation difficulties continue. Export orders expanded at higher rates. Price pressure remains strong, but the index saw its first expansion softening since November 2017. Demand remains robust, but the nation’s employment resources and supply chains continue to struggle. Respondents are overwhelmingly concerned about how tariff related activity is and will continue to affect their business,” says Fiore.

Of the 18 manufacturing industries, 17 reported growth in June, in the following order: Textile Mills; Wood Products; Nonmetallic Mineral Products; Printing & Related Support Activities; Electrical Equipment, Appliances & Components; Fabricated Metal Products; Computer & Electronic Products; Food, Beverage & Tobacco Products; Paper Products; Transportation Equipment; Furniture & Related Products; Machinery; Primary Metals; Miscellaneous Manufacturing; Chemical Products; Petroleum & Coal Products; and Plastics & Rubber Products. No industry reported a decrease in June compared to May. [49]

Technology Families

The PrecisionPath Roadmap focuses on portable spatial metrology instruments and supporting technologies. Members of the consortium have identified the following generic families of measurement technologies:

1. Laser Trackers
2. Laser Radars
3. Large and Small Volume Scanners
4. Portable Measuring Arms
5. Theodolites and Total Stations
6. Photogrammetry
7. Indoor GPS

Many portable spatial metrology instruments are used in the large-scale manufacturing industry. Photo Credit: New River Kinematics (NRK)

Much of the roadmap data was obtained from an industry-wide survey conducted by PPC. The survey was distributed electronically to expert users for a six month period and was also available to participants at the CMSC conference in July 2016. The PPC team analyzed the survey responses to identify important themes and trends, which motivated additional conversations with topical area experts to develop the results captured in this report.

The PPC team identified a set of attributes or properties that could be used to describe the usability and capabilities of each instrument family. These attributes were presented with a 5-point scale describing the quantitative or qualitative value for each attribute. Survey participants were asked to identify their estimate of the current value for each attribute, and the expected value 5 to 10 years in the future. The list of attributes and scales is provided below.

- Accuracy

  1 → < 10 microns (0.0004 in.)
  3 → > 250 microns (0.010 in.)
  5 → > 500 microns (0.020 in.)

- Measurement range

  1 → Contact
  3 → > 50 meters (~167 ft.)
  5 → > 100 meters (~333 ft.)

- Measurement speed

  1 → < 1 point/sec.
  3 → > 500 points/sec
  5 → > 1000 points/sec.

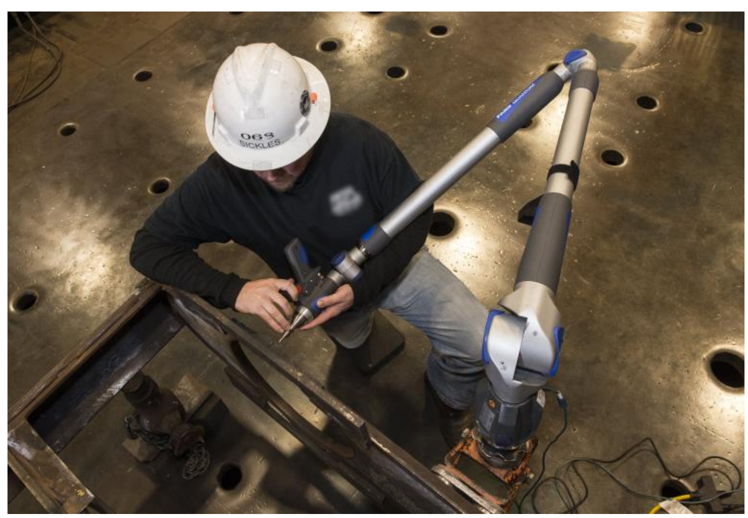


Photo Credit: Newport News Shipbuilding

- Environmental requirements

  1 → Minimal – may be used in uncontrolled environments
  3 → Moderate – used in typical HVAC environments
  5 → Significant – requires a tightly controlled environment

Technology Families (continued)

- Setup time

  1 → Minimal – instrument is fast and easy to move and setup
  3 → Moderate – moderate time and effort required to move and setup
  5 → Significant – substantial time and effort required to move and setup

- Versatility

  1 → Minimal – instrument best dedicated to a sole use
  3 → Moderate – instrument may sometimes be used for multiple tasks
  5 → Significant – instrument easily repurposed for multiple tasks

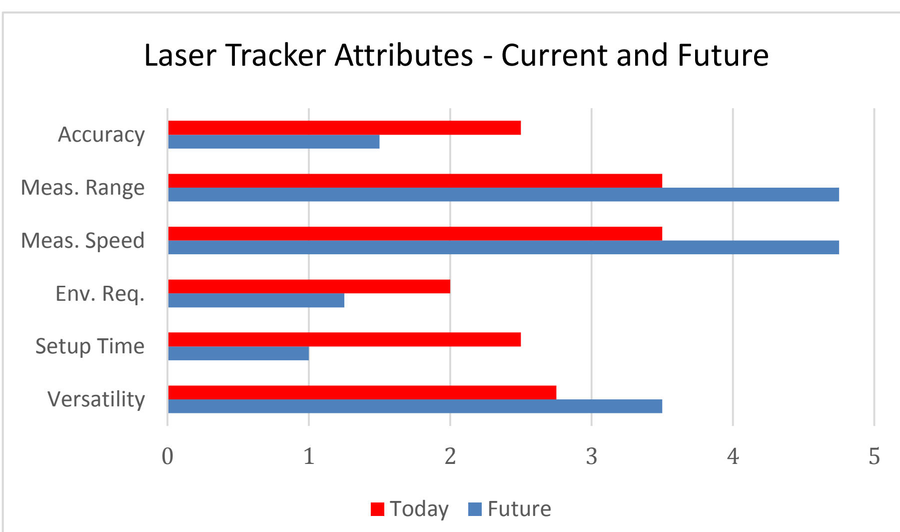
In addition to the numerical scales, participants could also provide textual responses to open-ended questions about what they liked most about the instrument(s) in each family of technologies, what they found most difficult or frustrating, and what new features and/or capabilities they would like to see implemented in the future. Participants were asked to only answer questions about technologies in which they had substantial hands-on experience or expertise in their applications. The results were analyzed and important trends were identified and reported below.

Lastly, for each technology family, the PPC team identified important ***initiatives*** that were scored on a Value vs. Difficulty scale to identify both critical tasks and low-hanging fruit. The Value score column reflects value from the perspective of the manufacturing organization, and the actual user of the equipment. The Difficulty score column reflects the expected difficulty of implementing the initiative from the equipment manufacturer's perspective.

1) LASER TRACKERS

Description of Current State and Future (10-Year) Needs of Laser Trackers

Laser trackers are among the most widely used technologies for portable spatial metrology. They are used in multiple industry sectors and for a wide range of measurement applications. The table below shows the mean value of responses from all survey participants regarding the current attributes of laser trackers and how they are expected to evolve into the future. Survey participants were also asked to identify the industry sector they represented, e.g. energy, transportation, shipbuilding, etc. When the responses are broken down by industry sector, the trends shown below are substantially the same.



Technology Families – Laser Trackers (continued)

Participants contributed the following text responses about laser tracker technology.

What do you like best about this technology?

- Speed and rich data sets.
- The measurement range, accuracy, and versatility of the tool.
- Ease of use, can take care of the majority of the tasks we have.
- Speed, accuracy, multiple configurations and accessories.
- Measurement profiles within the software to allow single operator. Watch window display for ease of feature based alignment.
- Accuracy of the instrument and versatility.
- Large envelope volume + accuracy.
- Accuracy, as well as real-time setting of components.
- It's ease of use, by far. I like the accuracy, all the in-process measurements functions (watch windows, on-site transformations, and visual checks with software view). The efficiency and speed of the tracker make it very user friendly.
- Ease of setup and compensation routines.
- Long range, dynamic measurement, accuracy, repeatability.
- The feeling of capturing a very accurate measurement of the system in question.
- Versatility, accuracy, reliability.
- It is such a versatile piece of equipment.
- Speed of data collection. It’s so easy to get accurate data!
- Portability Accuracy Speed.
- The versatility. Most any job we do can be done with a laser tracker. Also, the accuracy for jobs that require a high precision.
- Ability to see where measurements can be taken, and versatility of measurement modes.
- After the initial setup, data can be obtained and reported in a timely fashion. Everything works quickly and accurately.

What do you find most difficult or frustrating when using this technology?

- Harsh environments.
- The impact of air cleanliness and air movement on the beam accuracy and repeatability.
- I don't have any real issues with Laser trackers. I use other systems if the laser tracker is not the best approach.
- Line of sight issues.
- Gaining access for optimal line of sight.
- Maintaining a stable environment.
- Acquiring optimal targeting, software interfaces.
- Line of sight blocked, setup position not ideal to see features but options are limited on the floor, movement from air, floor or object.
- Placement and orientation of the SMRs.
- Set-up constraints related to cords and cables.
- The worst problem to run into with trackers tends to be areas where a solid base is available to setup.
- Initial set-up and validation/compensation that instrument is working at its peak.
- You have to deal with computer connectivity, which can be challenging. Older systems have old computer/components issues.
- Difficult equipment setups. Vibration, dirty environments, software interface.

Technology Families – Laser Trackers (continued)

- The setup of the instrument. Often the only way to measure something in shipbuilding is in a non-vertical position. Finding and making a proper fixture to safely mount the tracker can be difficult.
- Instability and vibrations when not set up in a vertical position. Required line of sight.
- The warm up time, and size.
- Due to the environment I work in, getting the instrument to the survey location.
- When the equipment does not function as intended or when it begins to vibrate due to harmonics of the setup.
- Vibration issues are probably the only frustrating thing about trackers.
- Losing drift due to environmental conditions.
- Laser trackers are a great instrument with high accuracy, but in the shipbuilding world, we have to work to ensure they are setup in the most stable manner we can. Vibration issues are probably the most frustrating part of the job. At times, we also have instruments that will not produce the back sight or angle accuracy checks that are satisfactory, even when properly compensated. These go back to our tool room for further inspection.
- Operators wanting to use T-Probe have repositioning/line of sight challenges.
- Sensitivity to fluctuating power sources, delicate tooling used, and long warm-up times.
- Learning the ins and outs of the software when not having the required training.
- In our work environment, the most difficult thing we deal with would have to be holding instrument drift. This is not due to the instrumentation, but the amount of construction held in a close range.

What are your future expectations?

- Laser trackers will take over with corner cubes moved around robotically and locating light scanning or scanning probes to have high data rates of data off of the part in long ranges (multi meters).
- Point cloud generation will be preferred, providing 10,000 data points per second to scan and align areal profile geometries and features.
- Articulated arms would be encoded again by spherical coordinate laser tracker metrology frames.
- Laser trackers need to be viewed as spherical metrology frames to locate mobile scanning units that are positioned robotically.
- I want to see laser tracker encoded location of point cloud data to course and fine measure precision features on a large part.
- The gap between data collecting, data processing and data reporting will be shortened.
- Measurement range: 30 meter plus systems yield same accuracy and speed as small volume systems.
- Speed: Speed must continue to increase for large scale process control at a rate of about an order of magnitude better every 5 years. Time is money and delays for measurement are not allowed or even understood. We see that features that make using instrument easier tend to decrease cycle time. An example is PowerLock on Leica laser trackers.
- Reliability: Equipment that doesn't need to be sent into a cal-lab for re-certification, especially the equipment that is stuck out in the factory doing in process measurements! Uptime guarantees.
- Accuracy: For technology like laser trackers, the accuracy should improve to meet some of the tighter tolerances.

Technology Families – Laser Trackers (continued)

Roadmap Vision Statement

The responses to the survey reveal that laser trackers are extremely popular and versatile instruments for a wide variety of measurement applications. The ability to achieve accuracy over long distances is one of the most important attributes for users, along with the ease of setup and use.

The most frustrating aspects of using laser trackers involved the requirement for line-of-sight access to features, the requirement for a well-controlled environment to obtain good results, and sensitivity to vibrations.

Based on an analysis of the responses above, we anticipate that in the next 5 to 10 years, manufacturers of laser trackers will focus on the following advances:

1. higher levels of accuracy, especially in less-controlled environments
2. less sensitivity to vibration
3. integration into automated measurement processes, which will also increase measurement speed
4. higher reliability and less downtime
5. establishment of a virtual metrology frame to tie together other measurement instruments that make local measurements over a smaller volume, and may be positioned robotically
6. better integration with processing and analysis software to enable near real-time reporting of results
7. wireless and cableless operation

Photo Credit: Automated Precision, Inc. (API)

Photo Credit: Hexagon Manufacturing Intelligence

Technology Families – Laser Trackers (continued)

Initiative Business Value vs. Difficulty for Laser Trackers

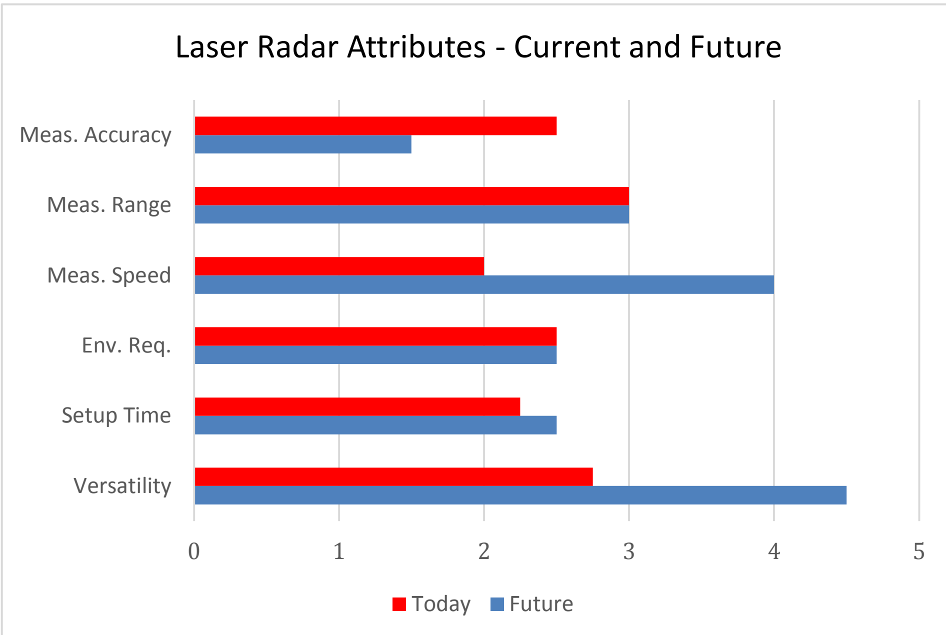
Based on an analysis of the data collected, the PPC team identified the following initiatives for supporting the evolving role of laser trackers in support of large scale manufacturing. The "Value" and "Difficulty" scores are based on a 5-point scale, with 1 representing low value and/or difficulty and 5 representing high value and/or difficulty. Value represents the importance of the proposed improvement in terms of ease of use, cost savings, time savings, or increased capability. Difficulty represents the expected time or effort required to achieve the improvement, including both technical and commercialization challenges.

Initiative	Business Value	Value score	Difficulty score
Identify best practices in the use of laser trackers	• Reduced training time • Improved productivity • Higher quality • Improved diffusion of laser trackers in the supply chain	4	1
Identify methods to specify and measure reliability of laser trackers	• Will facilitate development of more reliable laser trackers • Will increase use in in-process measurement and improve productivity • Improved return on investment • Will decrease rework due to not knowing when a tracker went out of tolerance	5	1
Improved maintenance/reliability	• Reduced down time • Improved productivity • Reduced maintenance costs	4	2
Increase accuracy of measurements	• Will allow measurements of higher tolerance features and dimensions • Increased measurement accuracy ratio • Meet design requirements	4	4
Develop laser trackers that are easier to use from a systemic standpoint – hardware and software	• Reduced training time - learning curve • Reduce set-up time • Reduction of cycle time – faster data collection • Less skilled/trained operators	4	3
Develop non-contact laser tracker	• Safety • Eliminates need to design SMR nests in hardware • Improves ease of use • Fragile SMRs no longer needed • Reduced risk of dropping SMR and FOD	5	5
Develop laser trackers that are less sensitive to environmental constraints such as temperature, humidity, and vibration	• Increased accuracy • Do not have to control environment • Can use outdoors in bright sunlight • Immune to changes in air current and humidity	5	5

Technology Families

2) LASER RADARS

Description of Current State and Future (10-Year) Needs for Laser Radars
Laser radar systems are currently not as widely used as laser trackers, but offer some notable advantages including: 1) non-contact and targetless measurement, 2) the ability to program specific regions for scanning/measurement, 3) the ability to control data point density, 4) edge detection features, 5) speed of data acquisition, and 6) the ability to measure large volumes by stitching data from multiple instrument positions. The table below shows the mean value of responses from all survey participants regarding the current attributes of laser radars and how they are expected to evolve into the future.



Survey participants contributed the following text responses on laser radar technology.

What do you like best about this technology?

- Non-contact measurements
- Versatility and ease of automation

What do you find most difficult or frustrating when using this technology?

- Size and wait. Current systems are extremely slow.

What are your future expectations?

- Size will reduce significantly, increasing portability and usefulness in tight spaces
- Systems will be able to track like a laser tracker, but will be targetless and able to make static or dynamic measurements in the sub-10 micron range

Technology Families – Laser Radars (continued)

Roadmap Vision Statement

The responses to the survey show underscore that laser radar systems are not as widely used as some other measurement technologies, due in part to the cost and physical size of the current systems. The ability to capture measurements without the need to move targets around on a part's surface is one of the most desirable features as per user feedback. Additionally, the other sought-after feature is the ability to automate measurements by programming which areas to measure along with control of the density of measured points. These popular attributes make laser trackers attractive choices for manufacturing environments with higher production volumes where repeated measurements of components or assemblies are required.

The most frustrating parts of using laser radars involved the requirement for line-of-sight access to features, the stipulation for a well-controlled environment to obtain good results, and the time required for setup and programming of measurements.

Based on an analysis of the responses above, we anticipate that in the next 5 to 10 years, manufacturers of laser radars will focus on the following advances:

1. higher levels of accuracy in less-controlled environments
2. reduction in size and cost
3. wireless and cableless operation
4. improved capability of analysis software or increased ability to integrate with popular third-party software packages
5. increased integration with vision-based tools to enable registration with global coordinate datums

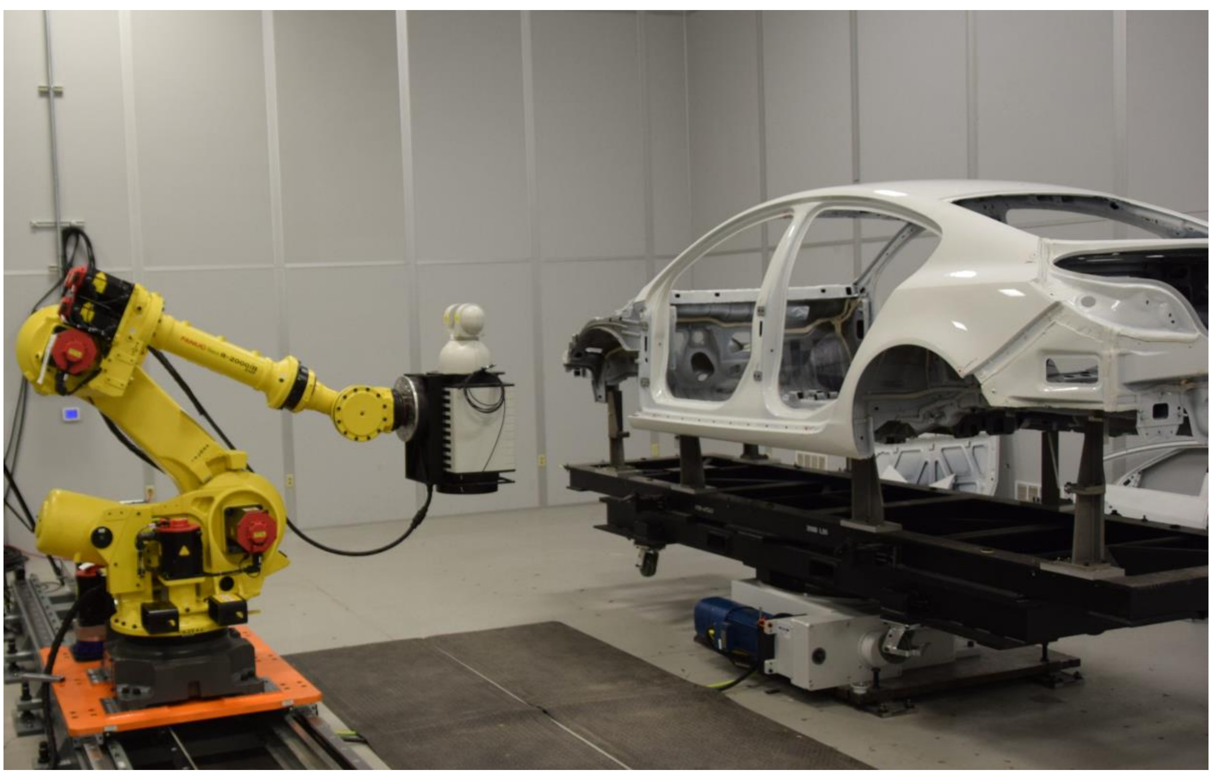


Photo Credit: Nikon Metrology

Technology Families – Laser Radars (continued)

Initiative Business Value vs. Difficulty for Laser Radars

Based on an analysis of the data collected, the PPC team identified the following initiatives for supporting the evolving role of laser radar in support of large scale manufacturing. The "Value" and "Difficulty" scores are based on a 5-point scale; with 1 representing low value and/or difficulty, and 5 representing high value and/or difficulty. Value represents the importance of the proposed improvement in terms of ease of use, cost savings, time savings, or increased capability. Difficulty represents the expected time or effort required to achieve the improvement, including both technical and commercialization challenges.

Initiative	Business Value	Value score	Difficulty score
Make laser radar instruments more portable	• Fewer operators/technicians needed to set up instrument • Current state large, heavy instrument has potential to cause back injuries • Can use laser radar in areas currently inaccessible to current state design	5	4
Lower cost of laser radars	• Lower cost	5	4
Improved accuracy and repeatability	• Will allow measurements of higher tolerance dimensions • Increased measurement accuracy ratio • Meet design requirements	4	4
Make instrument easier to use from a systemic standpoint – hardware and software	• Reduced training time - learning curve • Reduce set-up time • Reduction of cycle time – faster data collection • Less skilled/trained operators	5	3
Improved maintenance/reliability	• Reduced down time • Improved productivity • Reduced maintenance costs	4	3
Increase data collection speed	• Reduced cycle time • Increased point density • Minimize environmental issues	4	4

Photo Credit:

Nikon Metrology

Technology Families

3) LARGE & SMALL VOLUME SCANNERS

Scanners constitute one of the largest technology families in the marketplace. This technology family has a very large number of systems commercially available, and makes use of a wide variety of different technologies to enable spatial measurements. What scanners generally have in common is the ability to capture relatively dense point cloud data of part surfaces captured within their measurement range. Unlike laser trackers, they also do not require a cooperative target to be moved over the surface.

For this reason, there may be some ambiguity in determining which points in the point cloud belong to a feature of interest on the component being inspected. Modern software tools can help to automate the task of identifying which points in the point cloud belong to features of interest, but this capability is not inherent in the instrument itself. Scanners are the tool of choice for reverse engineering tasks, where the goal is to create a digital model of an existing, physical component or system. The dense point cloud that is generated by a scanner provides a good visual representation of the scanned object, and widely available software tools allow individual features to be identified and measured.

All scanners require "line of sight" access to perform their measurements. If all surfaces of an object are to be scanned, either the part or the scanner must be moved to multiple locations/orientations to perform a complete measurement. The point cloud data from each view position/direction must be merged together into a common coordinate system. This "stitching" of the data can be accomplished in multiple ways. One of the most common methods is to utilize multiple reference targets or features that are visible from all locations or directions of view. The reference targets may be affixed to the component being measured, or to the surfaces in the surrounding environment.

Another common method to stitch data is to use an external motion measurement device to measure the 6DOF motion of the instrument or target. Examples of this technique include the mounting of the part on precision turntables, or mounting of the scanning device on the end of a portable measuring arm. A third method used to merge data sets is to ensure substantial overlap in the individual measurement regions, and use optimization tools to find the 6DOF coordinate transformation to super-imposed points in the overlap regions. For the purposes of this roadmap, the Precision Path Consortium team has chosen to subdivide scanners into two sub-categories, large volume and small volume scanners.

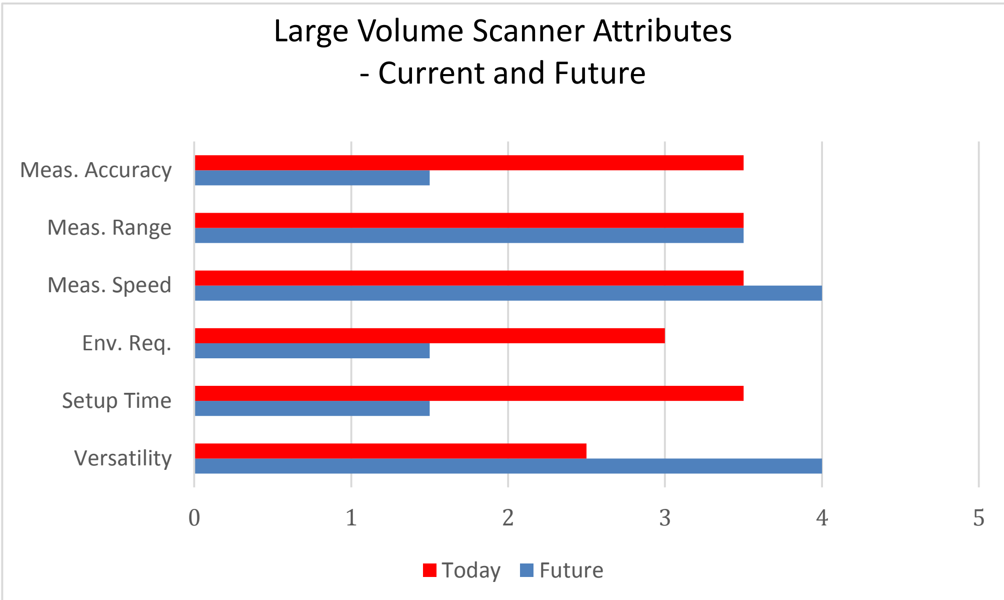
Description of Current State and Future (10-Year) Needs of Large Volume Scanners
Large volume scanners can measure surfaces areas of hundreds of meters, and generally rely on substantially different measurement approaches than small volume scanners. Large volume scanners generally project a single beam that can be steered over a large range of azimuth and elevation angles from the instrument. Various methods are used to measure the range from the instrument to the point where the beam intersects the measured object. Knowledge of the azimuth and elevation angles and the range provides the spherical coordinates of the point.

Large volume scanners can generally be programmed to survey a region in space defined by ranges of azimuth and elevation angles with a specified density of measured points within this region. It is clear that laser radars and total stations fall within this definition of large volume scanners. Although total stations do not require a cooperative target, they lack the speed and automation required to be considered scanners.

Photo Credit: AICON

Technology Families – Large Volume Scanners (continued)

Due to the capabilities and relative market penetration of large volume Scanners, the PrecisionPath team has chosen to recognize them as a distinct technology family category. The table below shows the mean value of responses from all survey participants regarding the current attributes of large volume scanners and how they are expected to evolve into the future.



Survey participants contributed the following text responses on large volume scanner technology.

What do you like best about this technology?

- Ability to see 3D deviations across the entire surface
- Ease of use
- Minimal extra equipment required for basic jobs
- Wow factor when customer see the data
- Ability to compare point cloud data to 3D CAD model of subassembly

What do you find most difficult or frustrating when using this technology?

- The ratio of range to uncertainty. We need to be able to scan over meters but have results with uncertainties at or below 10 um (3 ppm to 20 ppm)
- Need to acquire thousands to tens of thousands of data points like this in a matter of minutes
- Noise
- Battery life
- Too many options for data filtering
- Time required to register the data

What are your future expectations?

- The ever-improving scanning capabilities are key to large volume survey accuracy. Until it improves considerably, laser trackers and photogrammetry are the way to go today.

Technology Families – Large Volume Scanners (continued)

Roadmap Vision Statement

Large volume scanners will continue to play an important role in the manufacturing and assembly of large-scale products and systems. The development of documentary standards for this class of measurement instrument is underway as describe in the Standards section on page 53. The availability of such standards is expected to provide much-needed clarity to the market for both suppliers and users, and will likely result in an even wider usage of this technology family.

Photo Credit: Hexagon Manufacturing Intelligence

In the future, these systems will become more compact and easier to use, with wireless and cable-less operation becoming the norm. Storage and processing of the large volumes of data produced by these instruments will improve, along with tools and algorithms for pruning the data to maintain only what is actually necessary for the intended analysis. Integrated vision processing tied to coordinate data will enable easier visualization of data sets and the improved ability to tie individual data points to specific features. Instruments will become increasingly robust in addressing problematic colors and shininess of surfaces being measured.

Large volume scanners are expected to play a key role in manufacturing digitalization, as well as the establishment and maintenance of the "digital thread" that is a key aspect of Industry 4.0 initiatives and the Industrial Internet of Things.

Initiative Business Value vs. Difficulty of Large Volume Scanners

Based on an analysis of the data collected, the PPC team identified the following initiatives for supporting the evolving role of large volume scanners in support of large scale manufacturing. The "Value" and "Difficulty" scores are based on a 5-point scale; with 1 representing low value and/or difficulty, and 5 representing high value and/or difficulty. Value represents the importance of the proposed improvement in terms of ease of use, cost savings, time savings, or increased capability. Difficulty represents the expected time or effort required to achieve the improvement, including both technical and commercialization challenges.

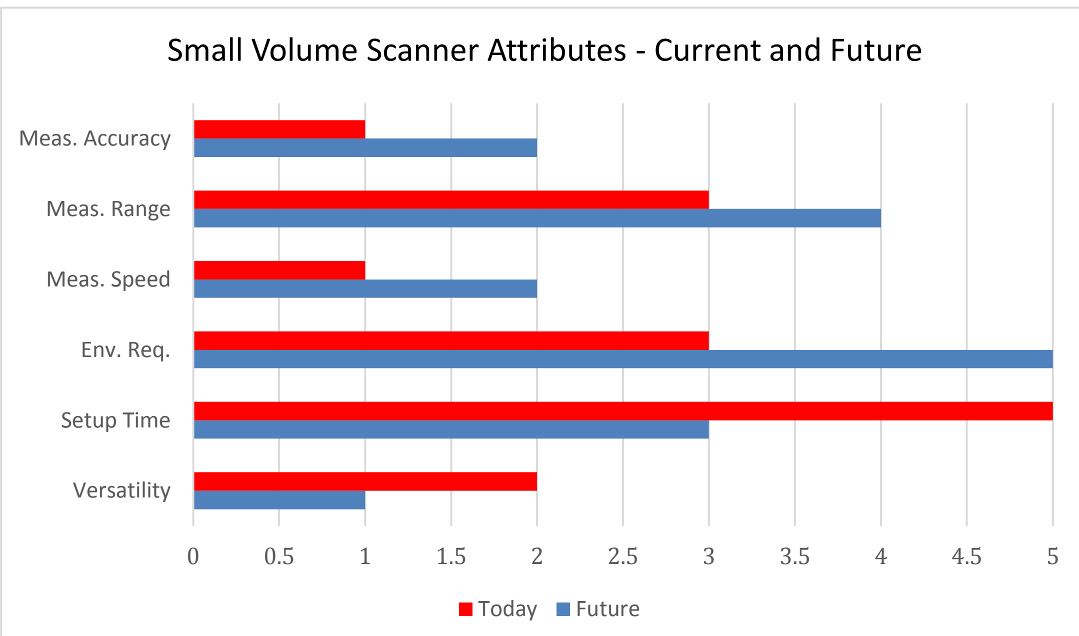
Initiative	Business Value	Value score	Difficulty score
Develop Scanner Standard	• Standardize best practices • Reduce incorrect data from improper use of instrument • Define acceptable data collection process	5	5
Increase accuracy	• Will allow measurements of higher tolerance dimensions • Increased measurement accuracy ratio • Meet design requirements	5	4

Technology Families – Small Volume Scanners

Current State and Future (10-Year) Needs of Small Volume Scanners
Small volume scanners can measure points on part surfaces up to a few meters from the instrument, although many commercial devices are limited to volumes much smaller than this. Many different technological approaches are used to acquire spatial measurements in small volume scanners, which generally rely on digital imaging in some form. One common configuration uses two digital cameras in a known spatial relationship to image the surface. For each point on the surface, if the corresponding pixel in each image can be identified, triangulation can be used to compute the spatial coordinates of the point.

Many commercial systems use a digital projector to project patterns onto the surface being measured that can be used to identify the pixels in each image corresponding to specific points on the surface. The use of triangulation calculations is one of the reasons why these scanners are generally confined to fairly small measurement volumes. In order to accurately compute coordinates of points that are many meters from the instrument, the cameras would also need to be separated by many meters, and their relative distance and orientation would need to be stable and well-known. Additionally, the imaging systems used by these instruments have a finite number of pixels, and the larger the field of view, the lower the resulting lateral resolution of the measurements.

The table below shows the mean value of responses from all survey participants regarding the current attributes of small volume scanners and how they are expected to evolve into the future. Unfortunately, only one participant elected this technology family, and they did not provide any text responses. Therefore, the data in the table below only reflects the views and opinions of a single person; and so care must be used in drawing conclusions from it.



Technology Families – Small Volume Scanners (continued)

Roadmap Vision Statement

Small volume scanners will continue to be a key tool for reverse engineering and measuring smaller components of large-scale systems. When combined with an external device to measure the 6-DOF location of the instrument as it is moved around a large component, portable or hand-held small volume scanners will also be used to digitize or measure larger components.

In the future, improvements in feature-based stitching will reduce or eliminate the need for targets. Instruments will become less sensitive to shiny or colored surfaces, eliminating the need for coating of parts prior to measurement. Because these instruments are largely vision-based, integration of photographic images with coordinate data will increase and will enable easier feature identification.

In the future, manufacturers will be able to seamlessly relocate small volume scanners between in-line, next-to-line, and offline measurement scenarios. These instruments will also be moved between product verification (GD&T analysis) and manufacturing control (SPC) applications. The small volume scanner will be routinely integrated with many other technologies into a single system or interface with them for real time data synthesis. Small volume scanners may find application for monitoring internal features on a layer-by-layer basis for additive manufacturing systems, and potentially even provide feedback to the machine for closed-loop control of part quality.

Photo Credit: Hexagon Manufacturing Intelligence

Photo Credit: Automated Precision, Inc. (API)

Technology Families – Small Volume Scanners (continued)

Initiative Business Value vs. Difficulty for Small Volume Scanners

Based on an analysis of the data collected, the PPC team identified the following initiatives for supporting the evolving role of small volume scanners in support of large scale manufacturing. The "Value" and "Difficulty" scores are based on a 5-point scale; with 1 representing low value and/or difficulty, and 5 representing high value and/or difficulty. Value represents the importance of the proposed improvement in terms of ease of use, cost savings, time savings, or increased capability. Difficulty represents the expected time or effort required to achieve the improvement, including both technical and commercialization challenges.

Initiative	Business Value	Value score	Difficulty score
Increased software power	• Ability to process large jobs – high volume of data • Increased capability	5	4
Robust storage of large volumes of data	• Reduced data loss • Easier archiving	4	3
Targetless measurement	• Decreased set up time	5	4
Reduced S/N ratio	• Decreased false points • Decreased data analysis time • Higher accuracy measurements	5	4
Improved equipment education prior to purchase	• Increased confidence that system will meet needs • Understanding of capabilities/limitations prior to purchase	5	1
Improved data analysis and reporting	• Decreased cycle time • Increased analysis capability • Clear reports – decreased time to interpret/understand	4	2

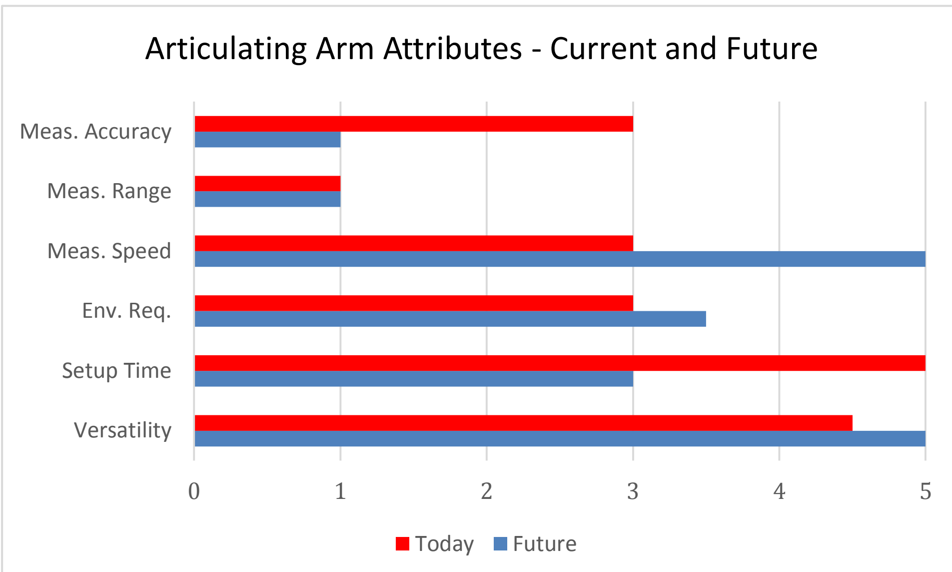
The Scanner technology family has a very large number of systems commercially available, and makes use of a wide variety of different technologies to enable spatial measurements.

Photo Credit: Hexagon Manufacturing Intelligence

Technology Families

4) PORTABLE MEASURING ARMS

Description of Current State and Future (10-Year) Needs of Portable Measuring Arms
Portable measuring arms (also known as articulating arms) are coordinate measurement machines (CMMs) widely used by a variety of industries. The instrument can address a broad range of measurement tasks provided that the physical size of the measured object fits within the work-volume of the device up to 15ft. Because of the relatively small measurement range, portable measuring arms have significant limitations for manufacturers of physically large systems, such as shipbuilding and aerospace. Currently, the portable CMMs are manually operated and are not used in applications where automation of measurement tasks is required. The ability to combine multiple probing/sensing modes, including tactile, light stripe, and areal scanning, is an attractive feature of the new generation of measuring arms. The table below shows the mean value of responses from all survey participants regarding the current attributes of portable measuring arms, and how they are expected to evolve into the future.



Participants contributed the following text responses on portable measuring arms.

What do you like best about this technology?

- Accuracy
- We can take point-to-point for precise measurements, scan a part for a better 2D profiles and laser scan a part for point cloud data, which can be used for reverse engineering and mapping data onto a CAD model.
- Speed & flexibility.

What do you find most difficult or frustrating when using this technology?

- Inaccessibility of surfaces or features
- Setting up the part in the allowable volume of the portable measuring arm
- Ergonomics

Technology Families – Portable Measuring Arms (continued)

What are your future expectations for Portable Measuring Arms?

- Measurement accuracy is expected to increase
- Measurement range has reached a practical limit and is not expected to increase significantly

Roadmap Vision Statement

The responses to the survey show that portable measuring arms are popular instruments that fill an important niche for accurate measurement over smaller volumes. Although the physical structure of the instrument can limit accessibility to certain regions of parts, the ability to reach features without line-of-sign issues provides an important advantage over other measurement technologies. The ability to combine tactile and non-contact sensing modalities provides important flexibility in measurement tasks and allows users to choose the mode that is most appropriate for their task.

The most frustrating parts of using portable arms involve the ergonomics of the instrument, and the effort required to ensure that the part is properly setup within the measurement volume of the instrument.

Based on an analysis of the responses above, we anticipate that in the next 5 to 10 years, manufacturers of portable measuring arms will focus on the following advances:

1. higher levels of accuracy, especially in less-controlled environments
2. improved ergonomics
3. integration of additional sensing/probing modalities,
4. improved software tools for setup and measurement planning
5. better integration with processing and analysis software to enable near real-time reporting of results of interest
6. wireless and cable-less operation

Photo Courtesy: Nikon Metrology


Photo Courtesy: UNC Charlotte

Technology Families – Portable Measuring Arms (continued)

Initiative Business Value vs. Difficulty for Portable Measuring Arms

Based on an analysis of the data collected, the PPC team identified the following initiatives for supporting the evolving role of portable measuring arms in support of large scale manufacturing. The "Value" and "Difficulty" scores are based on a 5-point scale; with 1 representing low value and/or difficulty, and 5 representing high value and/or difficulty. Value represents the importance of the proposed improvement in terms of ease of use, cost savings, time savings, or increased capability. Difficulty represents the expected time or effort required to achieve the improvement, including both technical and commercialization challenges.

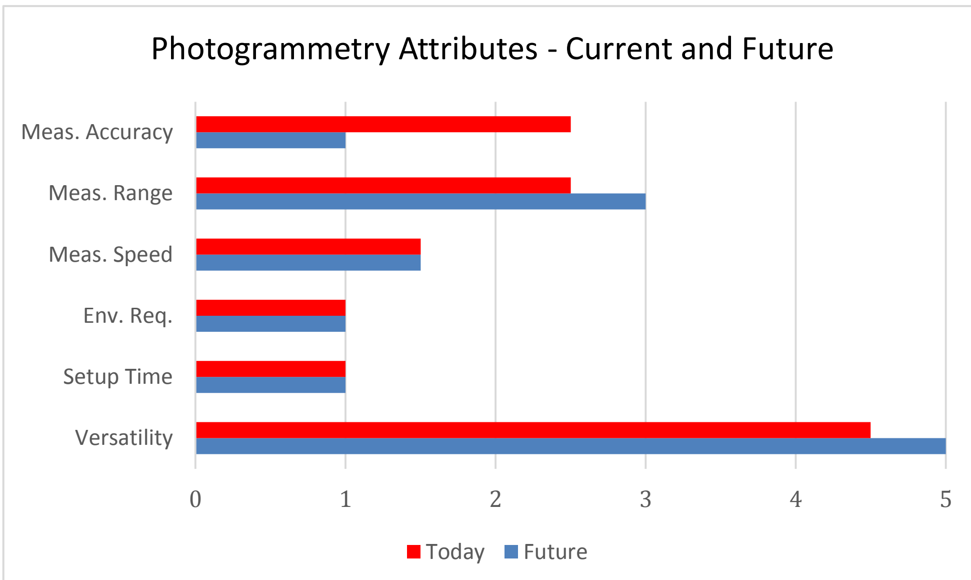
Initiative	Business Value	Value score	Difficulty score
Integrate with multiple devices	• Increase versatility of tool	4	4
Increase laser scanning capability – on par with probing	• Increase versatility of tool • Increase volume of data collected • Decrease error/noise	4	5
Increase volume of measurement with increased accuracy	• Ability to measure larger parts • Increased accuracy	5	3
Optical imaging and scanning	• Increase versatility of tool • Improved scan technique	3	4

Photo Courtesy: Coordinate Metrology Society

Technology Families

5) PHOTOGRAMMETRY

Description of Current State and Future (10-Year) Needs for Photogrammetry
Photogrammetry is one of the oldest large-scale, portable spatial metrology solutions. The advent of ever-improving digital photography technology, combined with dramatic increases in portable computing power, has resulted in modern photogrammetry systems that are easier to use, less expensive, and more accurate. Measurement accuracy is strongly related to pixel density within the field of view, and the development of digital cameras with higher pixel counts has helped to improve photogrammetric accuracy, particularly in industrial settings. The table below shows the mean value of responses from all survey participants regarding the current attributes of photogrammetry, and how they are expected to evolve into the future.



Participants contributed the following text responses on photogrammetry.

What do you like best about this technology?

- Portability
- Accuracy
- Ability to compensate for vibrations or movement of part
- Fast measurements, so minimal drift issues
- Does not require a large team to complete a survey

What do you find most difficult or frustrating when using this technology?

- Inconsistencies in flash levels
- Processing times for large jobs, especially with large numbers of pictures
- Clear line of sight required

What are your future expectations for photogrammetry?

- Measurement accuracy is expected to increase
- Data processing time will decrease

Technology Families - Photogrammetry (continued)

Roadmap Vision Statement

The responses to the survey show that photogrammetry continues to fill an important role in large-scale spatial metrology. Portability, rapid setup time, and low sensitivity to the environment are important advantages of this technology for users. The most frustrating aspects of photogrammetry for users involve obtaining correct exposure and flash level over the full field of view, line-of-sight requirements, and long data processing times.

Based on an analysis of the responses above, we anticipate that in the next 5 to 10 years, manufacturers of photogrammetry systems will focus on the following advances:

1. higher pixel count cameras to improve spatial resolution and accuracy
2. reduction or elimination of targets required for image registration
3. faster shutter speeds to enable monitoring of moving parts
4. faster data processing

Initiative Business Value vs. Difficulty for Photogrammetry

Based on an analysis of the data collected, the PPC team identified the following initiatives for supporting the evolving role of photogrammetry in support of large scale manufacturing. The "Value" and "Difficulty" scores are based on a 5-point scale with 1 representing low value and/or difficulty, and 5 representing high value and/or difficulty. Value represents the importance of the proposed improvement in terms of ease of use, cost savings, time savings, or increased capability. Difficulty represents the expected time or effort required to achieve the improvement, including both technical and commercialization challenges.

Initiative	Business Value	Value score	Difficulty score
Higher pixel count	• Increased accuracy	4	2
Limited targeting or targetless	• Decreased set-up time • Decreased FOD • Potential to capture more data	5	4
Improved field of view	• Increased data capture • Decreased data collection time	4	3
Improved shutter speeds	• Real-time data collection • Monitor moving parts	4	3

Photo Courtesy: Geodetic Systems

Photo Courtesy: Geodetic Systems

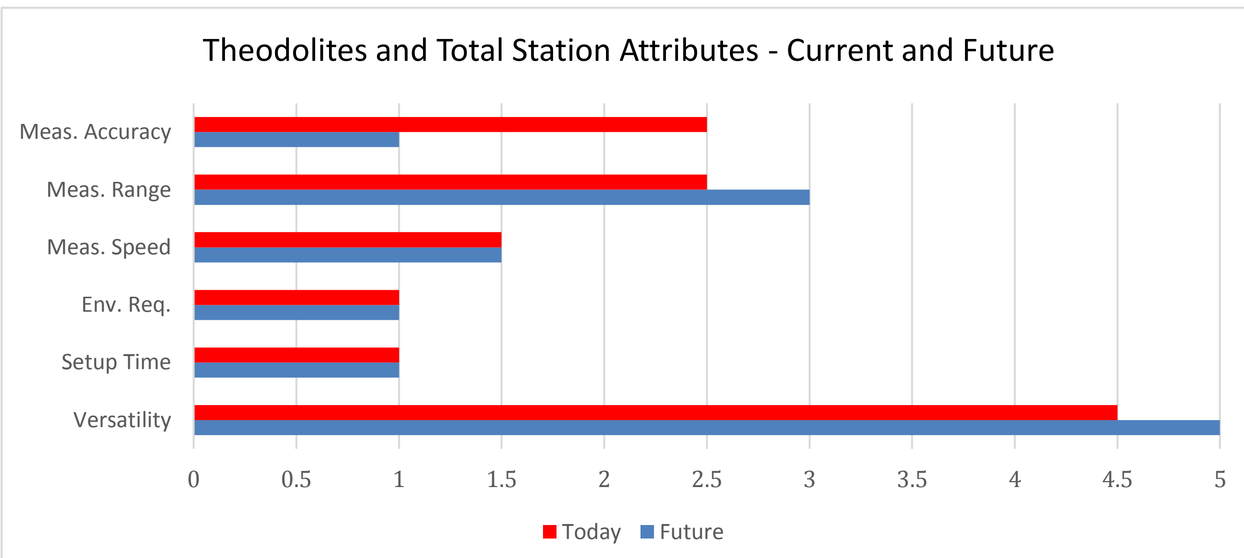
Technology Families

6) THEODOLITES & TOTAL STATIONS

Description of Current State and Future (10-Year) Needs for Theodolites & Total Stations
Theodolites and Total Stations were originally developed for surveying applications. Over time, these instruments have been adopted for large-scale industrial measurement applications. The instruments use a spherical coordinate system similar to laser trackers where an azimuth and elevation angle of the emitted beam are measured, and time-of-flight technology is used to measure the distance from the instrument to the point where the beam encounters the surface of the component.

The use of these instruments can be manual where the azimuth and elevation angles of the emitted beam are adjusted by hand. The systems can also be automated where the beam direction is automatically controlled. Theodolites and total stations can be used with a target retroreflector, similar to laser trackers. They can also be used in a targetless mode where the beam is reflected directly from the surface being measured. Modern Total Stations are capable of automatically following a moving retroreflector, similar to laser trackers.

The table below shows the mean value of responses from all survey participants regarding the current attributes of photogrammetry, and how they are expected to evolve into the future.



Participants contributed the following text responses on Theodolite and Total Station technology.

What do you like best about this technology?

- Rugged
- Light
- Able to work in more extreme conditions

What do you find most difficult or frustrating when using this technology?

- The amount of manual input needed compared to laser trackers

Technology Families – Theodolites and Total Stations (continued)

What are your future expectations for theodolites and total stations?

- Measurement accuracy is expected to improve
- Wireless operation will improve productivity

Roadmap Vision Statement

The boundary between Total Stations and Laser Trackers continues to narrow. In general, laser trackers are thought to be somewhat more accurate; while total stations are considered somewhat more portable and are designed to measure over larger distances with lower accuracy. Going forward, the distinction between trackers and the most advanced total stations will become blurred. However, it is expected that there will continue to be a market for lower performing and manual total stations due to the lower acquisition cost.

Initiative Business Value vs. Difficulty for Theodolites and Total Stations

Based on an analysis of the data collected, the PPC team identified the following initiatives for supporting the evolving role of theodolites and total stations in support of large scale manufacturing. The "Value" and "Difficulty" scores are based on a 5-point scale; with 1 representing low value and/or difficulty, and 5 representing high value and/or difficulty. Value represents the importance of the proposed improvement in terms of ease of use, cost savings, time savings, or increased capability. Difficulty represents the expected time or effort required to achieve the improvement, including both technical and commercialization challenges.

Initiative	Business Value	Value score	Difficulty score
Wireless communication	• Easier data collection • Decreased setup time	5	2
Increased total station accuracy	• Makes instrument more versatile • Can replace tracker in some situations	5	4

Photo Credit: Leica Geosystems

Photo Credit: Leica Geosystems

Technology Families – IGPS

7) IGPS

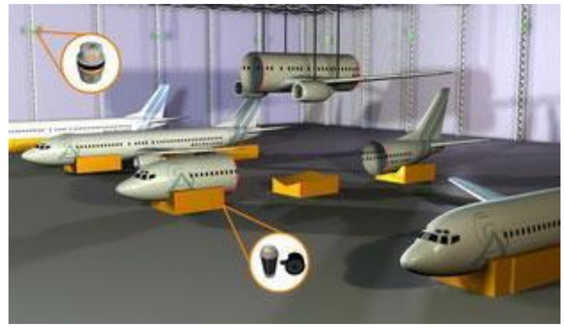


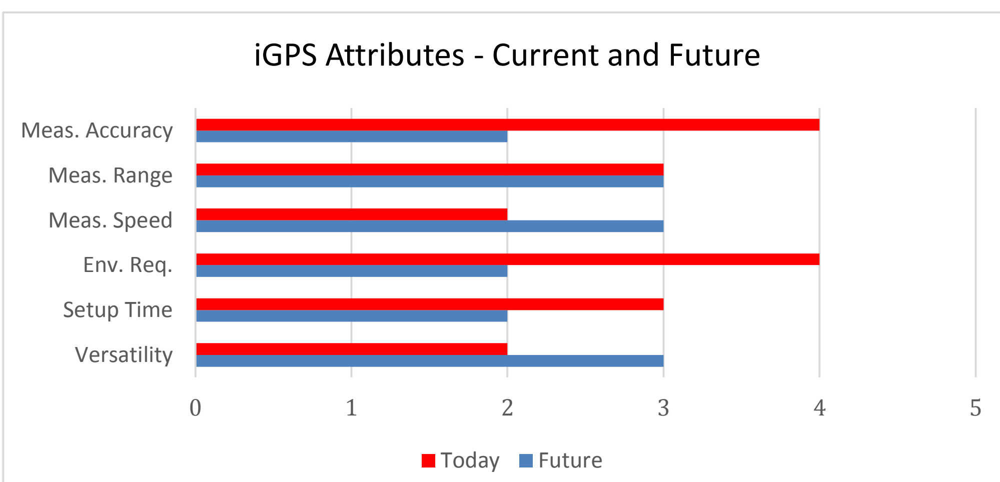
Photo Credit: Nikon Metrology

Description of Current State and Future (10-Year) Needs for IGPS
Indoor positioning systems are generally meant to mimic the capability of GPS for outdoor applications. A set of "transmitters" are fixed at stable locations within a building, and any number of "receivers" can be affixed to objects to be located or tracked. The transmitters may project radio frequency, optical, or even audio signals. The signals are sensed by the receiver (time of flight, time difference of arrival, or angle of arrival) from multiple transmitters to enable a trilateration or triangulation calculation to compute the spatial coordinates of the receiver relative to a coordinate system defined by the transmitters.

For many of these systems, reflections of the transmitted signals from other surfaces represents a serious challenge. This data may be interpreted as coming directly from the transmitter, resulting in erroneous data and errors in the computed position of the receiver. An additional challenge to commercial realization is that each installation requires its own set of transmitters. This scenario is unlike outdoor GPS where the satellite transmitters are government owned and maintained, and therefore defined for any commercial device under development. For indoor systems, the fragmentation in signal transmission technology has made it difficult for commercial developers to reach a critical mass of installed users.

Although there are many efforts in progress to develop commercial indoor positioning systems, most fall short of the accuracy needed for manufacturing and metrology. The best known of these systems is the *iGPS* system marketed by Nikon with a claimed typical accuracy of about 200 µm. Receivers mounted on the ends of hand-held probes enable tactile measurement of features in a manner similar to a portable measuring arm, but over a much larger volume.

The table below shows the mean value of responses from all survey participants regarding the current attributes of iGPS systems and how they are expected to evolve into the future. Unfortunately, only one participant elected this technology family. Therefore, the data in the table below and text comments only reflects the views and opinions of a single person; and so care must be used in drawing conclusions.



Technology Families - IGPS (continued)

The following comments were provided regarding iGPS technology.

What do you like best about this technology?

- The public interface to be able to develop own solutions

What do you find most difficult or frustrating when using this technology?

- *Software restrictions*
- *Traceability*

Roadmap Vision Statement

The intuitive appeal of indoor positioning systems is clear. One only needs to look at the wide variety of applications of GPS in outdoor applications to understand how a robust and sufficiently accurate indoor system would revolutionize the way measurements are made in manufacturing. Such a system could conceivably replace encoders and scales on machine tools, robots, and CMMs, and replace many other manual and automated measurement devices. If combined with RFID tags, the physical location of individual tools, inventory items, or raw materials could be tracked in real-time. It is expected that these systems will continue to improve in accuracy and speed, with the result that fewer technology approaches will remain viable. As the installed base grows, costs will decrease.

Initiative Business Value vs Difficulty for IGPS

Based on an analysis of the data collected, the PPC team identified the following initiatives for supporting the evolving role of indoor positioning systems in support of large scale manufacturing. The "Value" and "Difficulty" scores are based on a 5-point scale; with 1 representing low value and/or difficulty, and 5 representing high value and/or difficulty. Value represents the importance of the proposed improvement in terms of ease of use, cost savings, time savings, or increased capability. Difficulty represents the expected time or effort required to achieve the improvement, including both technical and commercialization challenges.

Initiative	Business Value	Value score	Difficulty score
Cellular based detection	• Controlled through mobile device • Easier to use	4	2
Microwave based detection	• Robust command	4	2
Higher accuracy, higher speed	• Increased accuracy • Increased capability – real-time data	5	4
Hand-held gauge detection	• Increased capability • Part inspection	5	3

Usage Scenarios

The PrecisionPath Roadmap focuses on portable spatial metrology instruments and supporting technologies. The consortium members have identified the following activities – which are referred to as "usage scenarios" that most often rely on these instruments. In each case, the usage scenario has the ultimate purpose of supporting manufacturing, either directly or indirectly:

- Calibration
- Alignment during Assembly
- Alignment with Machinery
- In-Process Measurement
- Post-Process Measurement
- Reverse Engineering

Photo Credit: Newport News Shipbuilding

As in the previous (Technology Families) section, much of the data on which this roadmap was based was obtained via a survey conducted by PPC. The survey was distributed electronically to expert users, and was also available to participants at the CMSC conference in July 2016. The PPC team analyzed the survey responses to identify important themes and trends; which then motivated additional conversations with topical area experts to develop the results shown here.

The attributes used to describe the attributes of each usage scenario use the same scale as the previous section, but here are intended to capture the relative importance and impact of these attributes on each use-case. For example, the setup time for an instrument may be relatively less important during the calibration of a large machine tool than when compared to the rapid setup needed for an alignment task in a manufacturing process.

For each usage scenario, survey participants were asked to relate the current importance of these attributes with expected values for 5-10 years in the future.

In addition to the collection of numerical data regarding the relative importance of various instrument attributes, the survey participants were giving an opportunity to identify the aspects of the usage scenario that were either notably enjoyable or satisfying, as well as those aspects that were particularly difficult or frustrating.

The numerical data are summarized in tables in each section, and selected comments are included as well. The PPC consortium members then reviewed the data and discussed appropriate initiatives that would improve the application of metrology equipment to the specific usage scenario. Value represents the importance of the proposed improvement in terms of ease of use, cost savings, time savings, or increased capability. Difficulty represents the expected time or effort required to achieve the improvement, including both technical and commercialization challenges.


Photo Credit: Verisurf Inc.

Usage Scenarios (continued)

4.1 Calibration

Description of Current State and Needs for the Future State (10 years)

Calibration as a usage scenario involves using metrology equipment to establish metrological traceability for either another instrument, a fixture (or other) gauge, a working standard, or other tooling or artifacts. The term calibration invokes traceability to the unit of length (the meter) as well as a statement of uncertainty. Calibration is critical to the manufacturing process because that lack of traceability prevents the user from making confident statements about the measurements, including determining if work is conforming or non-conforming.

The data collected during the survey indicate that this is a fairly mature field, with small changes expected in the various instrument performance metrics in the coming years.

Roadmap Vision Statement

An ongoing increase in the understanding of uncertainty and its role in calibration will allow manufacturing personnel to take more ownership of the calibration status of their tooling, jigs, and fixtures. While periodic external calibration may be needed on a longer-term basis, interim testing to confirm that manufacturing tools and equipment are within pre-determined limits. Better understanding of best practices, and methods to quantify calibration "quality" will need to be developed to support calibration in the next decade.

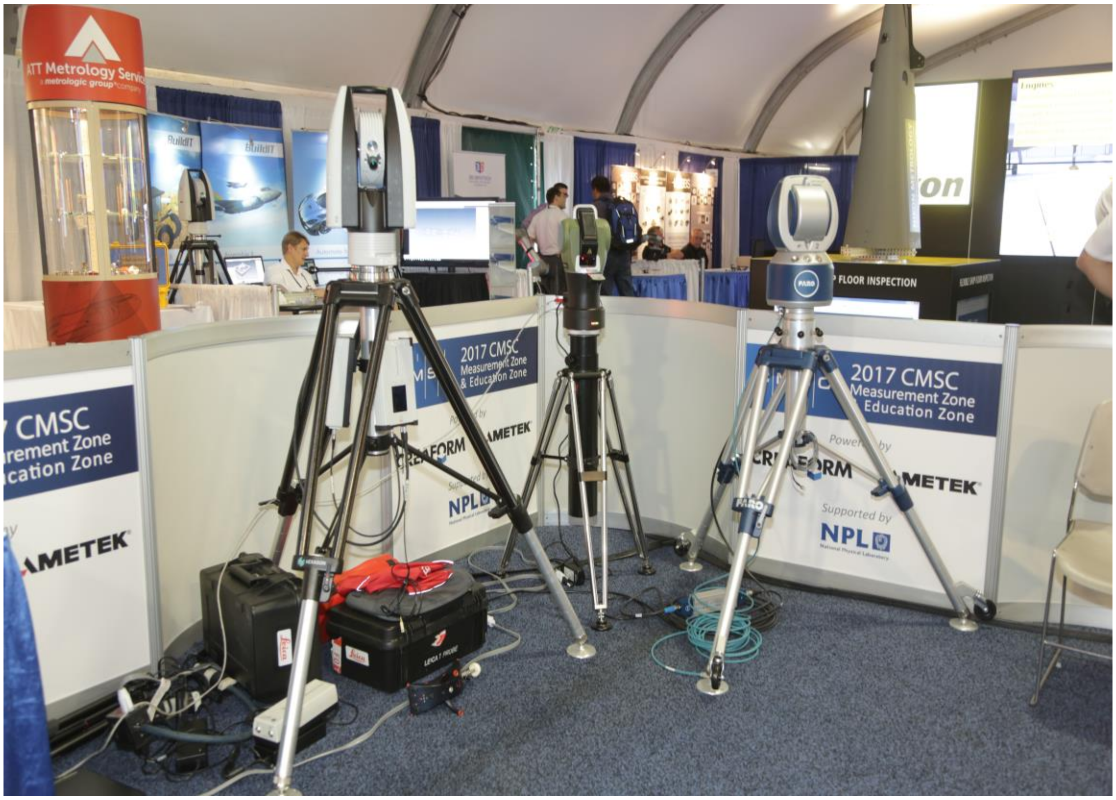


Photo Credit: Coordinate Metrology Society

Measurement Zone at the Coordinate Metrology Society Conference

Usage Scenarios (continued)

Initiative Business Value vs. Difficulty

In discussions with PPC experts, two initiatives were identified: the sharing of best practices in calibration techniques. While the small details of a calibration procedure may be proprietary from company to company, the broad methods and their benefits should be helpful to the entire large-scale manufacturing industry. This initiative would be paired with a more robust use of quantitative methods to evaluate the reliability of in-house calibration processes. This information could be used to guide scheduling of external calibration services, and prevent long-term use of instruments and tools that no longer meet their performance requirements.

Initiative	Business Value	Value Score	Difficulty Score
Sharing Best Practices in the use of Calibration	•Reduced training time •Improved productivity •Higher quality	4	4
Development of methods to specify and measure reliability of Calibrations	•Will facilitate more reliable calibrations •Supports an increase of in-process measurement to improve productivity •Smarter use of calibration resources	4	3

Photo Credit: Newport News Shipbuilding

Usage Scenarios (continued)

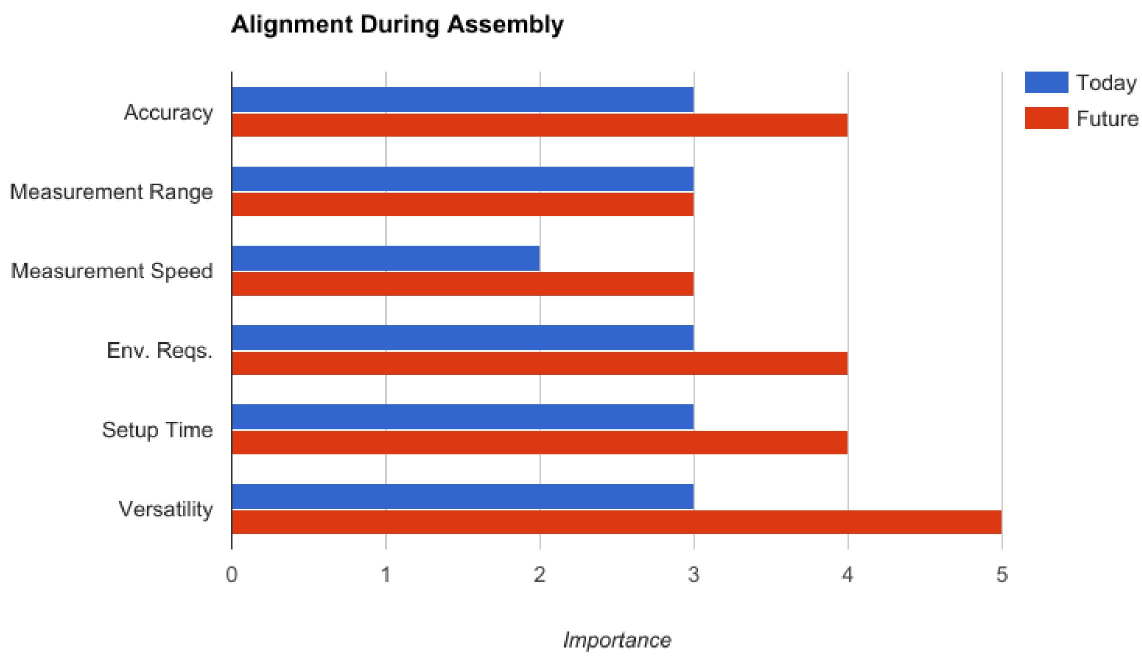
4.2 Alignment during Assembly

Description of Current State and Needs for the Future State (10 years)

Alignment of components during assembly is a common metrology practice and is normally done in real-time. This overlaps at times with jig building with the difference that these alignments are done on a part-by-part basis as part of the manufacturing cycle. Examples include the alignment of portions of a space craft or rocket using frame (6DOF) measurements of the two parts, the adjustment of the position of the rotor to the stator in a generator installation or repair, and others.

The enabling technology in these applications is often not the metrology instruments themselves, but the real-time integration of measurements of different components and the often complex analysis to produce information needed to move the parts closer together. These automation needs will continue to grow more important and high-precision assembly is used in more applications.

The survey summary data shown below reveal a consensus that almost all aspects of instrument performance will need to improve in order to support this higher level of automation.



Roadmap Vision Statement

The need to automate complex assembly processes with constant real-time feedback has been recognized for some time. Future systems will need to incorporate additional expert knowledge, such as instrument placement to insure line-of-sight to critical features during the entire assembly process. Better understanding and modeling of part distortion and deflections will be needed to ensure proper component placement with minimum additional measurements as support conditions change during the assembly process.

Usage Scenarios (continued)

Initiative Business Value vs Difficulty

The primary initiative that was discussed with the PPC experts was the use of prior information to better support assembly operations. With the advent of better computer modeling and point-cloud manipulation, it is easier to retain as-built geometry for components, which in turn reduces the need for extensive measurements during alignment. If the component geometries are known, then determining their relative locations can be done with fewer measurements than if the entire component geometry has to be re-measured during the process.

Initiative	Business Value	Value Score	Difficulty Score
Develop a system in which a subassembly variation is already in a database and is used to control positioning and optimization of the process	● Reduction of repeated measurements ● Planning of selective assembly when necessary	5	4

Photo Credit: Hexagon Manufacturing Intelligence

Usage Scenarios (continued)

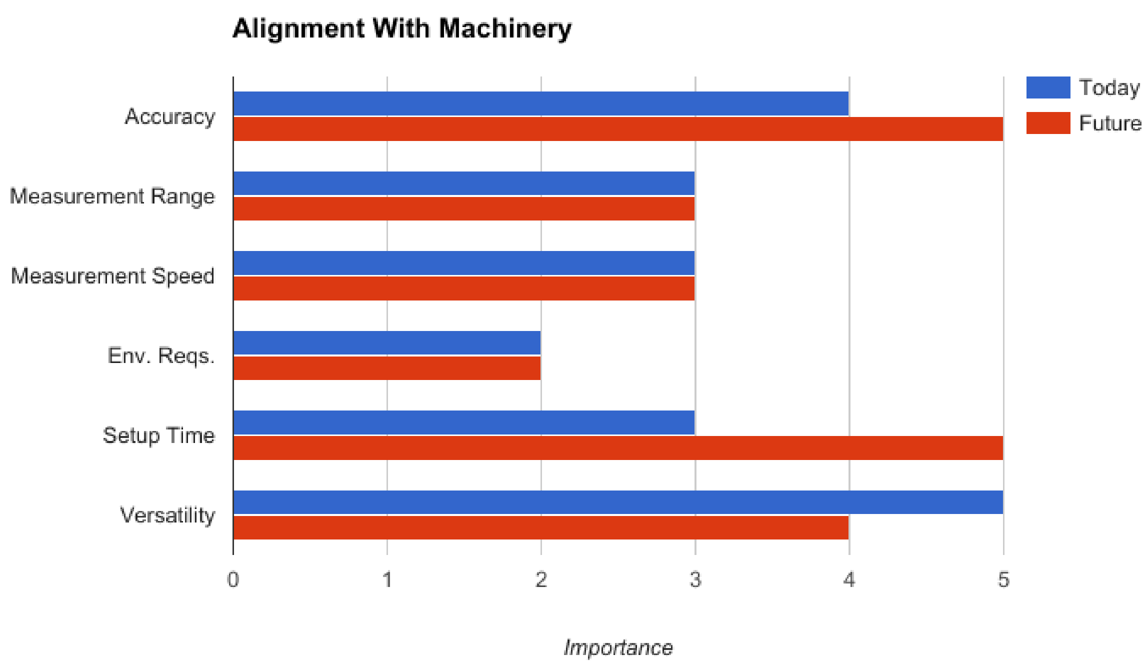
4.3 Alignment with Machinery

Description of Current State and Needs for the Future State (10 years)

Because of the need for dimensional traceability, Accuracy is one of the most important features of the existing Alignment (with Machinery) market space. This is evident in the survey data with an emphasis on accuracy in the future being one of the greatest areas of focus. One possible explanation for this future demand is the general trend of more challenging part tolerances. The machines that are required to match these enhanced tolerances will, in turn, need to be compensated with a more accurate measurement device. Another area of future focus identified by the survey is the setup time of the measurement device. Since downtime of production machinery is generally costly to a business, reducing the downtime is one of the most important endeavors for that business. Measurement equipment with reduced setup time will reduce machine downtime in two distinct ways:

1. Machine will be down for less time due to the setup of the device that is measuring the machine
2. Shorter measurement intervals will encourage more frequent checks thus offering prognostic data to reduce long-term failures and downtime

In this light, though the survey data do not necessarily indicate the importance, faster device measurement speed will contribute to reducing the overall downtime of production machinery and should be considered in parallel.



Roadmap Vision Statement

The accuracy of devices that are used for aligning machinery are already considered quite good. The industry should expect to serve the increasing demand for accuracy as part tolerances become more difficult to achieve. The main area of focus for equipment used in this type of usage scenario is setup time. The initiatives should be focused around ways to reduce setup time by improving hardware, software, and operator training.

Usage Scenarios (continued)

Initiative Business Value vs Difficulty

The primary initiatives discussed by the PPC experts include the implementation of standardized training programs that will not only increase the operator's ability, but will produce more uniform work product across the enterprise. This will improve overall machine performance by having a uniform process to ensure alignments are done the same way each time. In addition, improvements in both hardware and software will ensure that the mundane, repetitive tasks associated with alignment are managed in a repeatable way, leaving the operator free to perform more high-level auditing of data, and to look for outliers.

Initiative	Business Value	Value Score	Difficulty Score
Standard Training programs to improve operator ability	Improves setup time; Reduces machine downtime	4	2
Improvements in hardware to reduce human involvement in setting up instrument or measurement process	Improves setup time; Reduces machine downtime	3	3
Intuitive software to guide operators through measurements; Efficiency planning in measurement software	Improves setup time; Reduces machine downtime	5	3

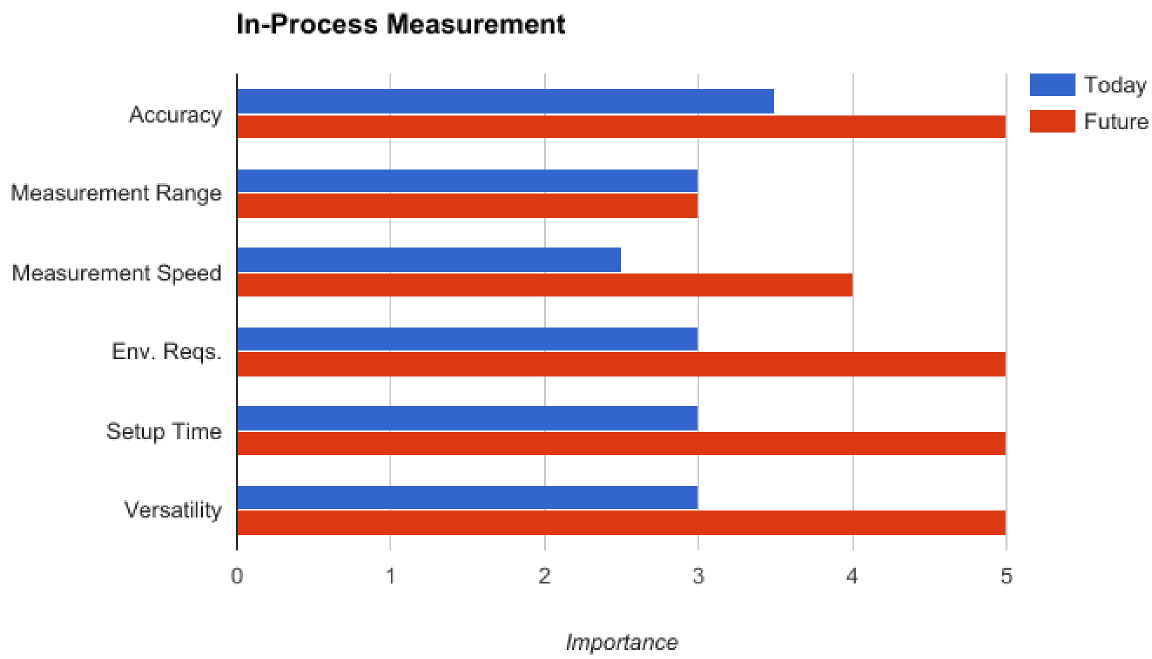
Photo Credit: Newport News Shipbuilding

Usage Scenarios (continued)

4.4 In-Process Measurement

Description of Current State and Needs for the Future State (10 years)

The underlying premise of statistical process control is that a well-controlled process will produce consistent parts. This requires a means to obtain measurement data during the manufacturing process to ensure the process performs as designed. In large scale metrology, the batch sizes are often small enough that this classical method of control is not appropriate. Instead, repeated measurements are taken as the product nears completion, ensuring adequate dimensional quality and preventing rework. This technique is particularly effective when it is difficult or impossible to move the part from manufacturing to inspection, or if the re-fixturing after inspection introduces significant risk of misalignment.



Survey data suggests that measurement technology will need to become more versatile and less dependent on environmental isolation to allow for more robust measurements in a shop floor environment. Demand for increasing manufacturing tolerances will continue to place more importance on the accuracy of the measurement instrument, a particularly challenging task when coupled with a decrease in environmental dependence.

Photo Credit:
Newport News Shipbuilding

Usage Scenarios (continued)

Roadmap Vision Statement

Both industry experts and the PPC survey indicate that this use case presents the biggest chance for future growth. Key initiatives such as the Smart Factory or Industry 4.0 are putting the pieces in place to move from post-process inspection to in-process inspection.

Initiative Business Value vs Difficulty

Performing in-process measurements necessarily means that the measuring equipment is on the shop floor, rather than a metrology lab. This means that the measuring equipment must be designed to be insensitive to the environmental conditions of the manufacturing environment, or that the shop environment is more tightly controlled. Additionally, measuring equipment must not only be able to communicate with quality personnel, but with other equipment in the manufacturing environment.

Initiative	Business Value	Value Score	Difficulty Score
Measurement equipment with less environmental sensitivity	More trust placed in measurements; Reduce reliance on redundant measurements	5	4
Improved interoperability of equipment	Measurement equipment that speaks the same language as other equipment in the production line	3	3

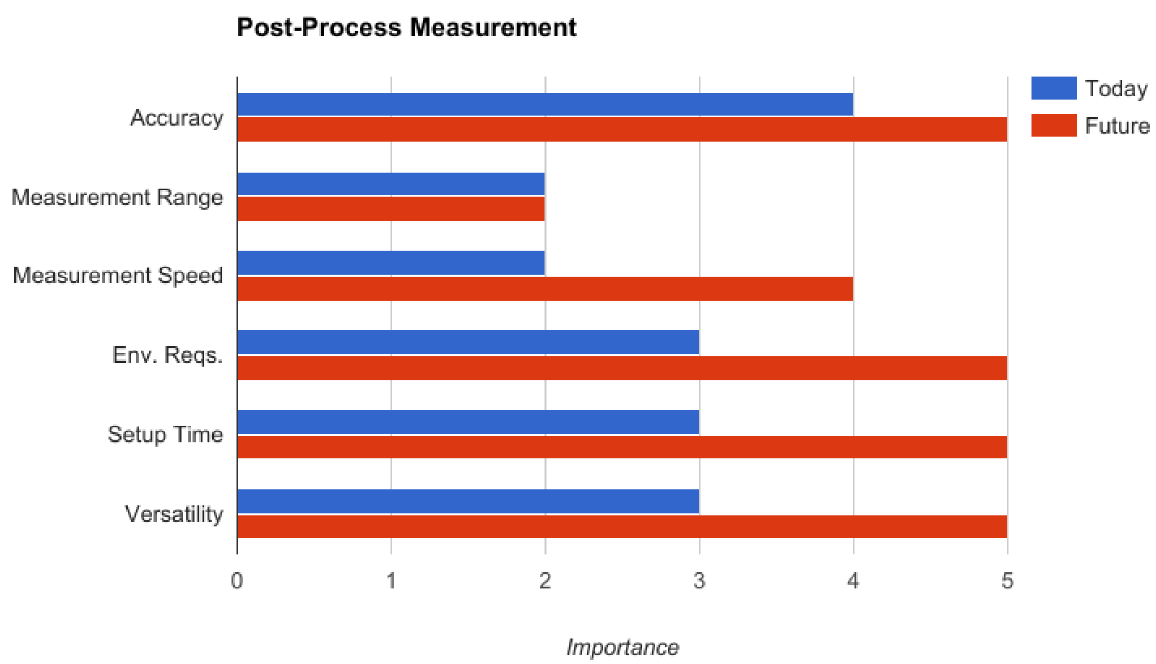
Photo Credit: Automated Precision, Inc. (API)

Usage Scenarios (continued)

4.5 Post-Process Measurement

Description of Current State and Needs for the Future State (10 years)

Post process measurement of product evaluates whether the product meets its geometric specifications. This is one of the most common usage scenarios for metrology equipment. Many industries have sufficient risk related to non-conformance so that 100% inspection is required for safety and regulatory reasons. While the uncertainty of the measurement results is becoming better understood, the drive for better measurements in a shorter period of time is relentless. Future aspects of this usage scenario will be a continued drive for faster, more accurate, more reliable data.



Like other use-cases, the survey data suggest that measurement range of existing equipment is adequate, while versatility, setup time, and dependence on environment should improve. Unlike other use cases, the future of Post-Process Measurement places greater emphasis on the importance of improving measurement speed. This logically follows from the idea that QC wants to ensure that all measurements are taken quickly, no data are missing, and that the part is cleared from production quickly. The sheer volume of participant comments reflects both that this is a very common application for users.

Roadmap Vision Statement

There will always be demand for post-process measurement in manufacturing. However, as in-process measurement becomes more commonplace, processes and technologies catering to post-process measurement will decline and eventually stabilize. Feedback from the Automotive segment suggest that many technologies are becoming more specialized and moving onto the assembly line to provide real-time measurement information for rapid quality assessment and Statistical Process Control (SPC). For Failure Modes and Effects Analysis (FMEA) and prototyping, industry experts suggest that there will always be demand for post-process measurement. The measurement technologies associated with post-process measurement are expected to become less specialized according to the PPC survey while increasing in accuracy of measurement. Measurement speed of associated technologies is expected to increase while setup time is expected to decrease to allow operators to report quickly.

Usage Scenarios (continued)

Initiative Business Value vs Difficulty

Although the initiatives may seem a bit generic, the drive for increased versatility and greater speed in measuring instruments is too strong to ignore. The industry as a whole seems satisfied with the data coming from their current instruments, but is cognizant of the need for increased integrity of the measurement data.

Initiative	Business Value	Value Score	Difficulty Score
Equipment with greater versatility	Less capital assets -- one technology to do more	3	3
Equipment with greater measurement speed	Less time spent in QC; Quicker reaction to failed parts	5	3

Photo Credit: Verisurf Software, Inc.

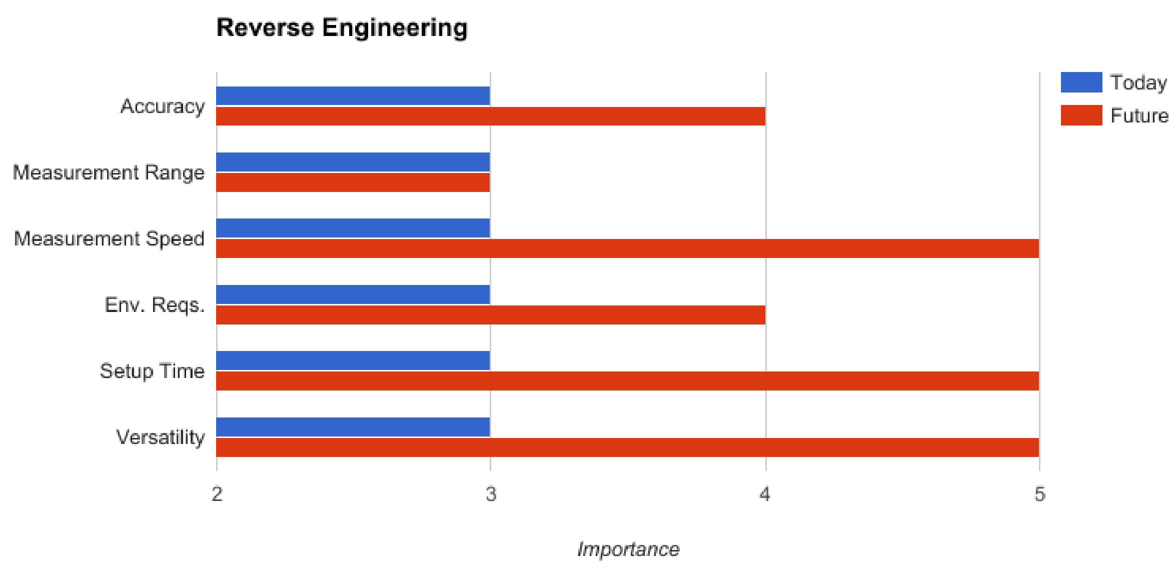
Photo Credit: Hexagon Manufacturing Intelligence

Usage Scenarios (continued)

4.6 Reverse Engineering (RE}

Description of Current State and Needs for the Future State (10 years)

The increased availability of high-speed point cloud measuring systems and supporting software has made it easier for users to capture data from surfaces for which there is no existing model. The creation of the part model from these point coordinates is often referred to as "reverse engineering." The required quality of the model produced may vary with industry and application, but as a minimum requirement, a complete "airtight" model is often required. As the modeling software becomes more sophisticated, the demands on the point-collection instruments become stronger. The table of survey data below shows the consensus of users regarding the importance of instrument performance improvements needed to support this usage scenario.



Roadmap Vision Statement

Demand for Reverse Engineering is expected to increase as more parts and components are moved into the Digital Thread. A potential driver for increasing this demand is additive manufacturing -- enabling rapid manufacturing and remanufacturing of broken/fatigued components. The operator still remains an essential cog in the machinery of Reverse Engineering as RE still heavily relies on human interpretation of measurement data. It is expected that RE will be simplified tremendously by artificial intelligence and machine heuristics that are a primary area of focus in manufacturing production. Improvement in this use case will tied heavily to the technologies that are used to acquire large amounts of surface -- and eventually sub-surface -- measurement data. 3D volumetric scanners, photogrammetry, 2D Machine Vision, and CT scanning are critical technologies that are tied to the future of this field. As part tolerances become tighter, the measurement technologies required to capture data for the purpose of RE will need to be tighter.

Usage Scenarios (continued)

Initiative Business Value vs Difficulty

The primary initiatives identified by the PPC experts were the needed improvement in measurement technologies (whether in raw instrument performance or in better software support) and additional capability in the software to produce surface models with less human intervention. These initiatives share the goal of reducing the routine work needed from an operator, and in turn improving the repeatability of measurement results by reducing the human interaction in the measuring process.

Initiative	Business Value	Value Score	Difficulty Score
Better heuristic analytics to interpret measurement data and create surfaces/meshes	Reduces human intervention and cost; improves speed and consistency of producing models; Enables potential "Rapid Remanufacturing"	4	5
Measurement technologies with less noise and better accuracy	Improve out-of-the-gate measurements with less "massaging"	4	3

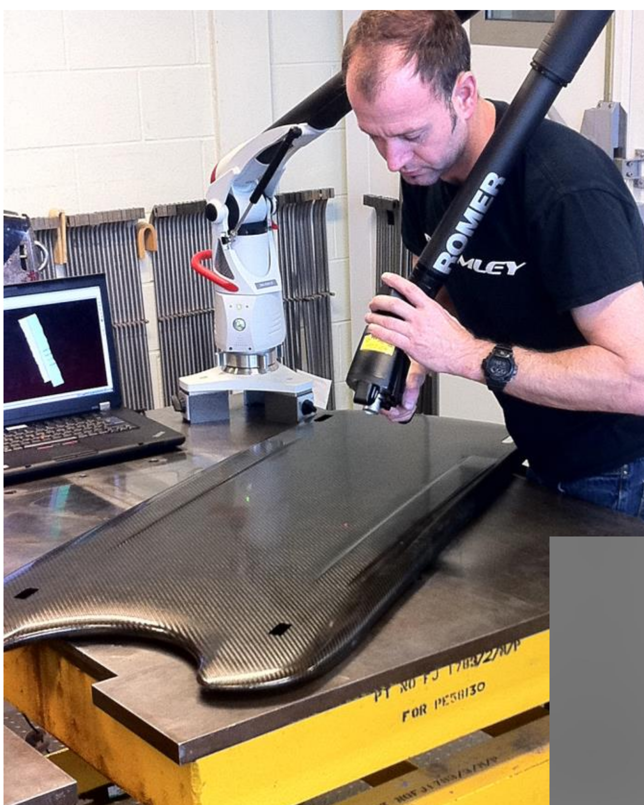
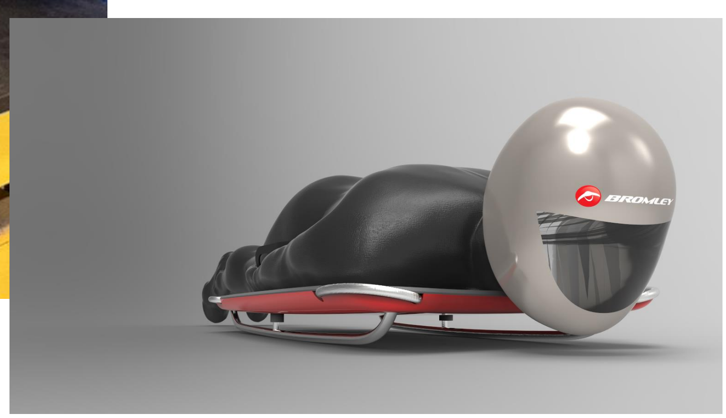


Photo Credit:
Hexagon Manufacturing Intelligence



Standards

The fields of manufacturing and measurement are filled with standards: standards describing product performance, standards for workplace safety, standards for the ecological impact of waste materials. This section of the roadmap describes the standards and standardization efforts most relevant and – where absent – most needed for the continued improvement of metrology's support of manufacturing.

Description of Current State and Future Needs (in 10 years)

The current state of the standards landscape is that mature technologies – such as articulating arm CMMs and Laser Trackers – have documentary standards that describe performance evaluation tests for these instruments. This allows instrument manufacturers to specify the "accuracy" of the instruments, and for their customers to periodically evaluate the instruments to ensure continued performance.

The short term (3-5 years) future will see an increased focus on standardization for all aspects of the measurement process. Not only will the instruments meet standard specifications, but the data produced from measurement will need to meet standard reporting requirements and the operators of the instruments will have standard competence requirements established through certification programs.

In the longer term (10 years) we envision standards forming a more uniform and comprehensive set of specifications. In order to support manufacturing, more integrated documentary standards must be used to ensure commonality of requirements from design to final product.

Standards Identified

In the PrecisionPath Needs Assessment Workshop held in Charlotte, and in subsequent working group meetings, the following standards and classes of standards were identified as being important to the support of large scale precision manufacturing.

1. Scanner Standards
   Laser scanners allow the collection of dense clouds of data over large volumes. Because of the type of data collected, current standards that describe point-to-point measuring performance are not suitable for testing the instruments. This segment of the instrument market is growing very quickly, and the need for a comprehensive test of these instrument's performance is needed. Recent work on this type of standard is underway in the ISO TC172 SC6 and in the ASTM E57-02 committees. The latter group has recently published the standard ASTM E3125-17, *Standard Test Method for Evaluating the Point-to-Point Distance Measurement Performance of Spherical Coordinate 3D Imaging Systems in the Medium Range*.

2. In-Process Checks
   Much of large-scale metrology is performed in an environment that is either uncontrolled, or poorly controlled when compared to a laboratory environment. In addition, some measurement setups can take from several hours to several days to perform. To mitigate the influence of the changing conditions over these time periods, interim or in-process checks must be performed to assure the accuracy of measurement. While most instrument manufacturers have proprietary routines that may be run to reset compensation parameters, there is a need for a standard procedure to provide quantitative verification that the compensation is effective. One such procedure is outlined in NISTIR 8016 – "*A Proposed Interim Check for Field Testing a Laser Tracker's 3-D Length Measurement Capability Using a Calibrated Scale Bar as a Reference Artifact.*" This document provides a set of tests that can be performed by laser trackers in the field. What remains is the adoption of this test, or a

Standards (continued)

similar test, as part of a standard, so that users will be able to track instrument performance to a standard test. Additionally, the extension of this test in a way that is suitable for other (not laser tracker) instruments is also needed.

3. Post-processing and Data Fusion
   A characteristic of large-scale metrology is that data from multiple instruments are often used to produce a single coherent collection of measurement results. Dense scanning data may be interspersed with higher-accuracy network points, or sparse data from a more accurate instrument. Various algorithms are used to merge data from different instruments, and to filter these data to remove outliers and redundant points. The methods by which these processes are accomplished are proprietary to individual software, and the uncertainty in the data manipulation may contribute significantly to the end measurement result. While some standards exist for evaluating simple fitting algorithms, such as ASME B89.4.10 *Methods for Performance Evaluation of Coordinate Measuring System Software*, there are no standards for how complex fitting of data clouds could be evaluated.

4. GD&T Update
   Geometric Dimensioning and Tolerancing (GD&T) is the language that allows designers to specify the allowable geometric variation in parts and assemblies. This is important to the metrology community for two reasons. The first reason is that GD&T describes what must be measured and whether a given geometry is acceptable or not. The second reason is that the magnitude of the tolerances specified will often determine what measuring equipment may be used, as the uncertainty of the measurements obtained with an instrument should be significantly less that the tolerance for that part characteristic.

   The main ASME standard for GD&T, Y14.5, is undergoing revision and is expected to be released in late 2018 or early 2019. This is a very mature standard, and the release of a new revision is not expected to dramatically affect industry. The changes to the standard are expected to be minor, with the intent of clarifying existing concepts in the standard.

5. User Certification Standard
   Greater complexity in both product designs and inspection technology have made the profession of metrologist more demanding, and the identification and evaluation of the appropriate skills for coordinate metrology professionals has long been an important, but moving, target. The coordinate metrology society (CMS) has developed certification credentials for both *Level-One Certified Portable 3D Metrologist*, and for *Level-Two device-specific certifications*.

   A preparatory course for the Level-One certification has been developed jointly by ECM – Global Measurement Solutions and the National Physical Laboratory (UK). The course and the certification exam provide a path for 3D metrologists who wish to obtain certification of theirs skills and knowledge. This certification effort within CMS continues to grow, with an examination in fixed CMMs nearing completion.

6. Reporting Standards
   More instruments and supporting software are used in metrology than ever before. This has resulted in a wide variety of different reporting methods. Different reporting schemes can result in confusion for the end user, and the need to standardize reports has been recognized for some time. As an example, the content and formatting of First Article Inspection reports is described in AS9102, the North American aerospace standard for *First Article Inspection Requirements*. In relation to GD&T requirements, a standard is being developed within Y14 Subcommittee 45: *Measurement Data Reporting Practices*. The success of these standards will depend on the industry needs for automation, balanced against the desire to have custom or proprietary reporting.

Standards (continued)

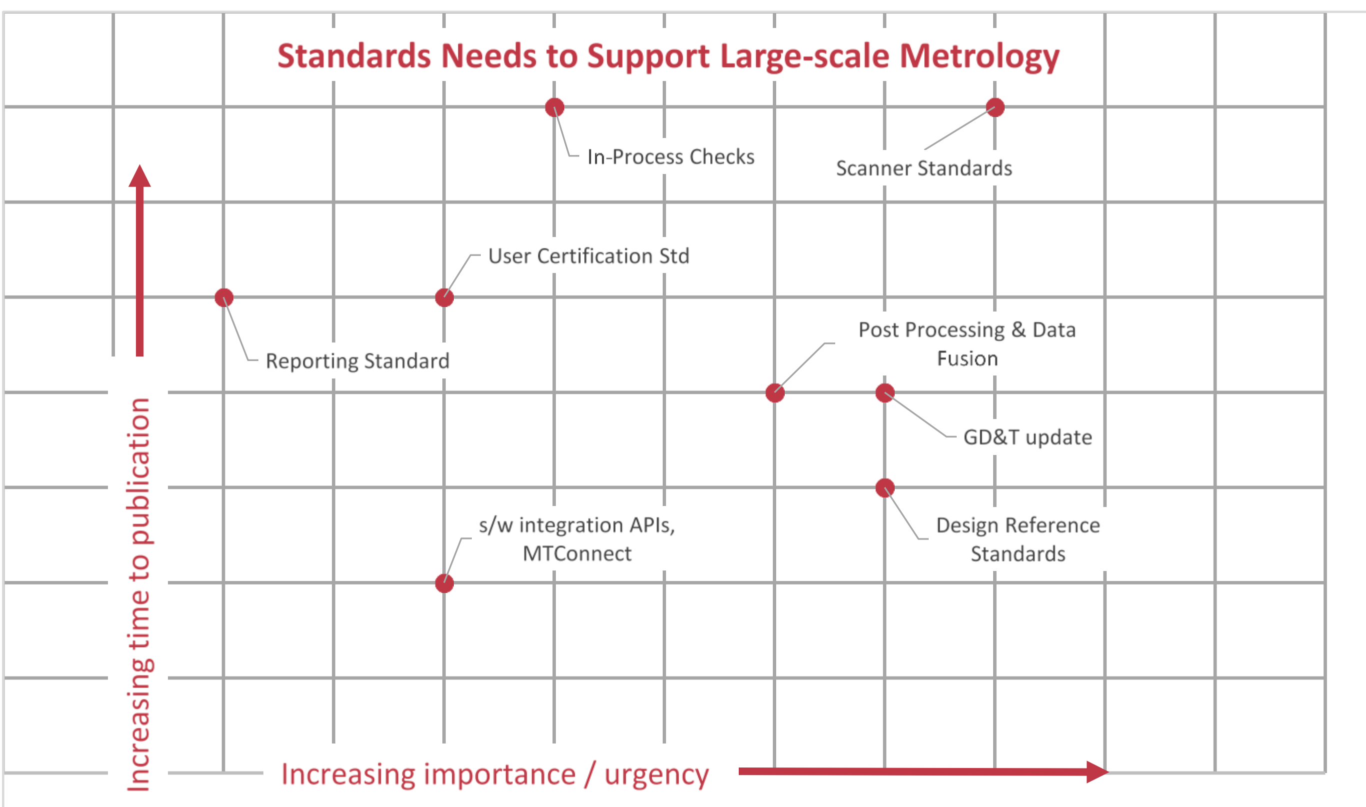
7. Software Interoperability Standards
   An increased demand for automation in manufacturing has placed similar demands on metrology to support manufacturing. Automation is most successful when all of the processes are able to communicate with one another, and interoperability is the mechanism that allows both manufacturing systems and metrology tools to communicate with each other and with higher-level systems, such as enterprise resource planning (ERP, ERP II) tools. Two notable standards in this area are MTConnect, which standardizes the way that manufacturing equipment can report their status and "health" and the Quality Information Framework (QIF) which provides standardized templates for moving information related to quality throughout the part lifecycle from design to manufacturing to inspection. Both of these standards are available free of charge from their respective development organizations (mtconnect.org, qifstandards.org).

Roadmap Vision Statement

Standards of the future will become more and more interwoven, and instrument performance standards may require that the results of testing be reported according to other data integration standards. The evolution of GD&T will interact with how designers convey their designs as well as the training requirements for operator certification. Standards may also become more 'granular' as different implementations of technology permit (or require) differing measurement strategies. Finally, a requirement of some data-modeling standards (QIF is one example) will be that the actual contents of the standards be computer-readable, so that the implementation of the standard can be accomplished directly by the processors performing the data analysis.

Priority and Time of Development Table

The various standards were discussed at length during the Needs Assessment workshop and the experts present were polled to determine the relative importance of having various standards, as well as the anticipated timeline for the emergence of these standards. While the importance scale is a relative one, the time scale in the figure below ranges from 1-2 years (imminent) to 6-8 years (work just beginning).



Data Management

For the purposes of this roadmap, data management is defined as the administrative process by which the required data is acquired, validated, stored, protected, and processed, and by which its accessibility, reliability, and timeliness is ensured to satisfy the needs of the data users.

All portable metrology instruments, regardless of the details of how they operate, rely on software to perform their measurement functions; and create data sets that need to be stored and analyzed. This software may be provided by the instrument OEM, or increasingly by 3rd parties. Regardless of the source, the software performs one or more of the following functions:

- User interface for planning the measurements
- User interface for operation of the instrument
- Control and management of instrument settings and functions, including calibration
- Conversion of raw transducer signals into coordinate data
- Filtering and smoothing of data

Once data is collected, it needs to be validated, stored, protected, processed, and analyzed to extract information of interest. These operations are very often performed by the software developed by 3rd parties. Examples of softwares used in conjunction with portable metrology instruments include:

- OEM specific
- 3rd party
- Metrological evaluation of GD&T specifications
- CAD
- Spreadsheets
- Point cloud manipulation
- Reverse Engineering
- Variation analysis
- Trend analysis
- Database tools
- Robotics and automation

It is apparent that without appropriate software to support these functions and tasks, none of the measurement technologies addressed in this roadmap could exist or function. From the end-user's point of view, software-enabled advances in functionality or ease-of-use may be more important and valuable than advances in hardware capability.

Description of Current State and Future Needs (in 10 years)

Current State

The current state of data management and software is characterized by the following general observations:

- Multiple software packages are often required to get the job done. Data analysis tasks may be highly specific to particular industries and/or projects; and the native software provided by the instrument OEM may not have the capability to perform these analyses. Furthermore, if a company owns metrology instruments from many different OEMs, each will likely have a different software package to support it; resulting in operators needing specialized training on each, and no commonality in data formatting and no interoperability.

Data Management (continued)

- There are currently no clear standards defined for data interoperability between software programs. This leads to a situation where additional, customized "post-processing" software may be needed to translate the data produced by an instrument into a form that can be used by another software tool.
- Many of the software programs currently in the market are "niche" products designed to address a specific task for a specific user or group of users. Users of these products can become locked into a particular technology or operating system version unless the vendors of these packages have the resources and ability to continually update them as technologies evolve.
- Most software packages are the result of years of cobbling together features demanded by the largest users. This can lead to inefficiencies in how the software operates, gaps in capabilities, rapidly expanding challenges in maintenance.
- Software development can be instrument driven, often resulting in excessive focus on a particular new capability offered by that instrument rather than ensuring broad ability to perform a full range of metrology tasks.
- Current software solutions require skilled operators with substantial training and experience. In general, the user interface is not intuitive, and differs substantially from instrument to instrument and vendor to vendor.
- Current software tools do not provide much in the way of automated assistance based on embedded expertise to users. Therefore, users must not only become proficient in the use of the software, they must also possess a high level of knowledge about metrology in order to obtain the best quality measurements.

Roadmap Vision Statement

Going forward, software and data management advances are expected to be more important and dramatic than hardware advances, which are inherently restricted by the physics of the instrument. These advances will be driven by a number of trends and emerging drivers.

1. *Merging of multiple software's into a single package*.
   Metrology software will follow the trend of engineering software used for design and analysis, where multiple software packages and tools are merged into a single large package. This will reduce or remove problems with data interoperability for tools within the larger package, and will increase efficiency for users of the data. Increasingly, metrology software tools will also merge with design and analysis packages to create a seamless interface between design, engineering, and manufacturing.

2. *Development will be driven by software companies, not just to support a particular piece of hardware*.
   Future software tools for metrology will be capable of working equally well with a wide variety of instruments and technologies. Software developers will utilize a broader view of metrology, manufacturing, and the entire engineering enterprise to structure their software to be able to operate efficiently within the larger context. Increasingly, metrology software will provide developer platforms to support APP-based add-ons from 3rd party developers. This will enable a much wider variety of customized tools and solutions to be developed, without requiring the software company to provide all of the resources necessary to develop and support them.

3. *Clear standards for data interoperability.*
   Metrology data will increasingly be utilized for a variety of purposes to support the "digital thread" that is the backbone of the emerging Industrial Internet of Things (IIoT). Standardization of data formats and structures and smooth interoperability is necessary for the digital thread to become a real and useful tool to support advanced manufacturing.

Data Management (continued)

4. *Streamlined, easily searchable, simple HMI's that require little to no training.*
   Human-machine interfaces (HMI) in metrology software have not kept pace with developments demonstrated in personal computing, smart phones, social media, etc. HMIs will increasingly "guide" the user through the process of setting up instrument and taking measurements, instead of simply offering a multi-tiered menu structure that requires users to not only be familiar with where to find the menu item they need, but also to have substantial expertise with the instrument and its proper operation. Future software will embed expertise that reduces the requirement for operators to make expert decisions as they make measurements.

5. *Cloud based storage and collaboration*
   The emerging digital thread dependent on relevant data is easily and quickly available to all who require it, while still maintaining appropriate security. Future software will increasingly support this cloud-based storage and collaboration.

6. *Customer driven, flexible licensing*
   As metrology software becomes increasing more powerful and complex, the cost of the software increases. Customers seek flexible licensing arrangements that allow them to access infrequently used features at a cost proportional to their pattern of usage.

7. *Easy automation controls – robotics – machine interfaces*
   Metrology tasks will become increasingly automated in the future, and the software that controls and operates the instruments will be required to quickly and easily integrate with robotic devices and other manufacturing cells.

8. *Voice integration*
   Voice recognition has made tremendous strides over the past years, and is now integrated into a wide variety of consumer devices to enable easier access and control of those devices. In the future, metrology software will incorporate voice integration to enable easier and faster setup of measurement devices and plans, and to enable single operators to issue commands to the software during a measurement activity without walking back to the computer.

9. *Augmented and virtual reality*
   Immersive technologies such as augmented reality will begin to appear in metrology software. This will allow users to "see" instructions and guidance during measurements, and will enable immersive experiences where the user can "walk through" virtual, as-built components and assemblies that are based on metrology data.

Photo Credit:
Automated Precision, Inc. (API)

Data Management (continued)

Initiative Business Value vs Difficulty

Based on an analysis of the data collected and discussions with experts, the PPC team identified the following initiatives for supporting the evolving role of laser trackers in support of large-scale manufacturing. The "Value" and "Difficulty" scores are based on a 5-point scale; with 1 representing low value and/or difficulty, and 5 representing high value and/or difficulty. Value represents the importance of the proposed improvement in terms of ease of use, cost savings, time savings, or increased capability. Difficulty represents the expected time or effort required to achieve the improvement, including both technical and commercialization challenges.

Initiative	Business Value	Value Score	Difficulty Score
Merging of multiple software's into 1	• Streamlines the process	3	4
Development driven by software companies and not hardware companies	• Better feature for the End User, not the Hardware Salesperson. Real data	5	1
Clear Standard for Data Interoperability	• Makes it easy to transfer data with little or no translation	3	5
Simple to use – No train	• Anyone can pick up the tool	3	3

Photo Credit: Verisurf Software, Inc.

Workforce Development

Description of Current State and Future Needs (in 10 years)

Workforce development is critical in order to complement the technology-related initiatives in this Roadmap. It is vital to nurture a workforce that is aware of and interested in industrial metrology.

Historically, Industrial Metrology is a career more by chance than by choice. Job descriptions are not standardized and Wages and salaries are not defined by any established levels of skill or competencies. Currently, manning projections for the industry are not established or published. Institutes of higher learning are not actively engaged in establishing 3D Metrology curriculums.

The necessity of establishing job qualifications could be encumbered as well as wage standards are too broad within the current competitive market. The Metrology industry needs the U.S. Board of Labor acceptance which is vital to the continued efforts to increase awareness of the industry's growth.

The metrology services market is expected to increase its worth to $824.6 million by the year 2020 with an estimated Compound Annual Growth Rate (CAGR) of 7%. The projected growth is due to the rise in demand from end-users specifically in the market for precise inspection methods. These industries include manufacturing, energy, electronics, and automotive. Increased innovation and the technology are also factors contributing to the industry's growth. Independent solutions in combination with the use of more efficient equipment has seen a rapid increase that is also projected to continue.

Roadmap Vision Statement

Clear job descriptions for metrology are established and recognized in some companies or organizations. Additionally, some companies, organizations, technical schools and universities have established educational plans for the industry.

Unfortunately, the Department of Labor does not recognize the metrology industry, or specifically the large-scale 3D metrology industry. Because of this lack of acknowledgement, there are no clear job classification parameters or recognized salary ranges. This issue creates a major problem throughout the Unites States in terms of defining the labor needs to maintain this important skill set.

Based on research and limited data in this area, the consensus of the PrecisionPath Consortium is the expectation of 30% growth in the metrology workforce in the next decade. These next-generation jobs will require different skills for greater productivity in large scale manufacturing.

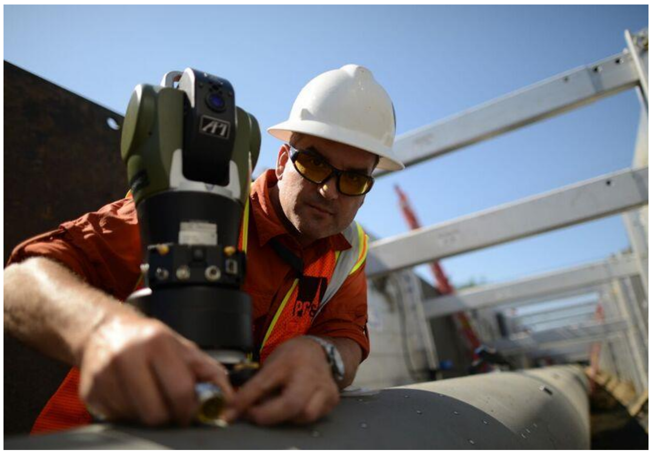


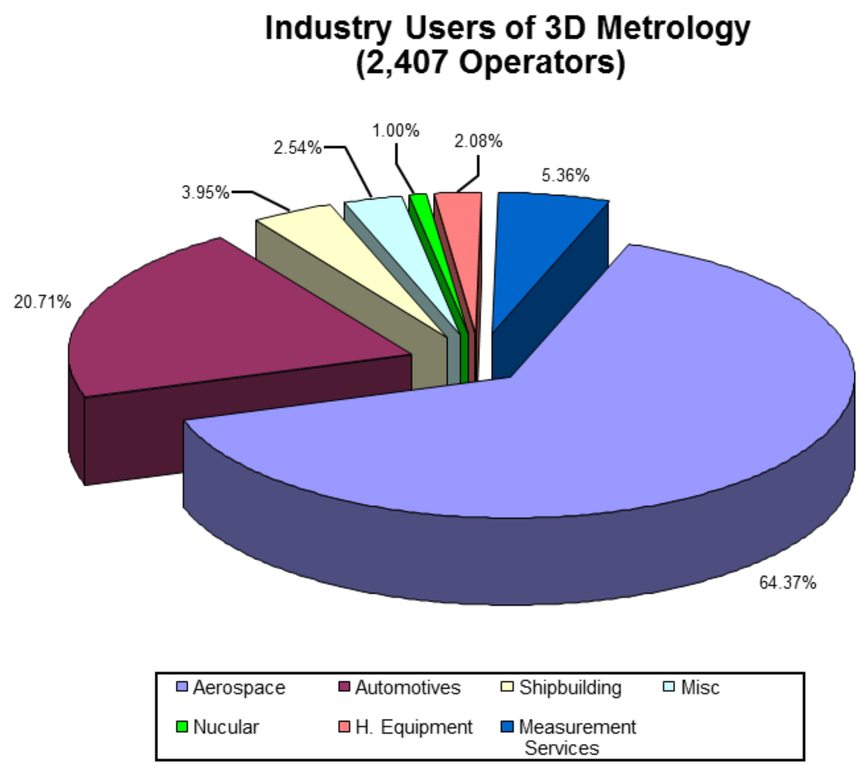
Photo Credit: Automated Precision, Inc. (API)

Photo Credit: Newport News Shipbuilding

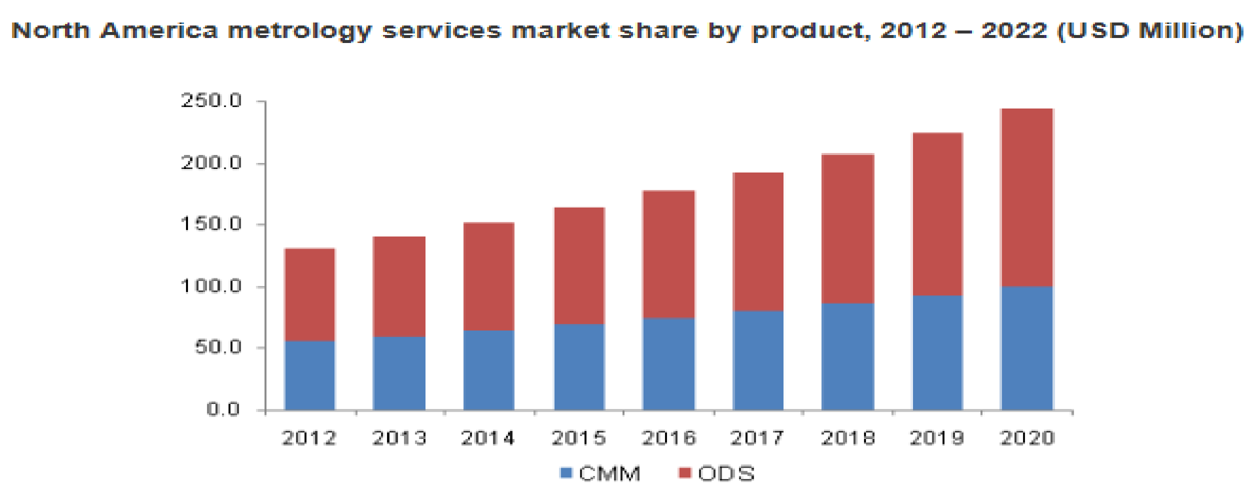
Workforce Development (continued)

Market Data for 3D Metrology Industry

The graphs shown below are an indication of the scarcity of market data concerning the state of the industry. The following table depicts the estimated number of operators using 3D Metrology equipment and their industries throughout the United States. Clearly this survey drastically under-represents the total number of users of 3D metrology



SOURCE: Grandview Research

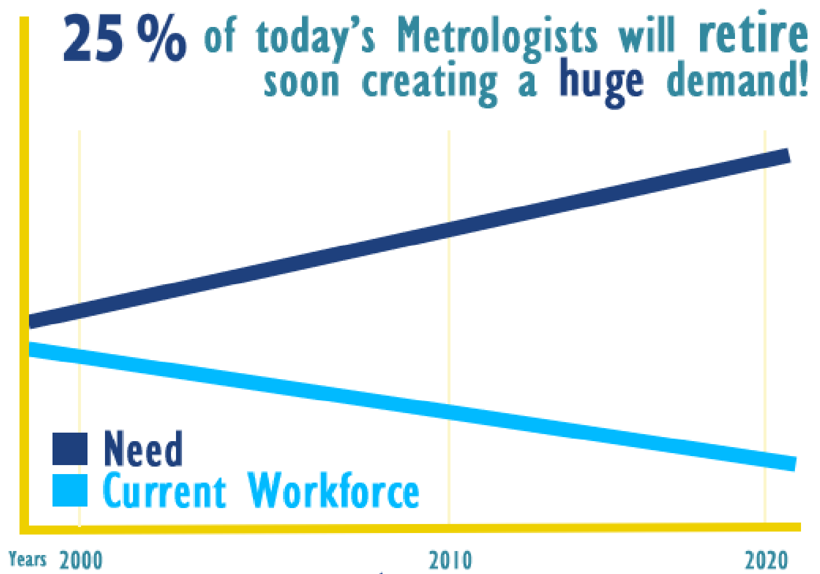


According to Grandview Research, Optical Digitizer and Scanners (ODS) and Coordinate Measurement Machines (CMM). ODS is anticipated to account for approximately 60% of the market in 2020.

Workforce Development (continued)

Initiative Business Value vs Difficulty for Workforce Development

Initiative	Business Value	Value Score	Difficulty Score
Create videos depicting use of "cool" laser trackers or other technology	Helps attract young workers who are interested in a technology-based career	**5**	2
Survey OEM's, Metrology companies, universities and trade magazines to get a better read on the demographics of industrial metrology in the U.S.	Helps to better define the state of the industry and gives a path forward.	**5**	3
Engage CMS in collaboration with the Dept. of Labor and existing universities and colleges that have a metrology programs to define and establish a clear job definition and requirements for an "industrial metrologist".	Brings a continuity to the problem and creates a "one voice" by which improvements in recruitment, retention, wage setting and education can be centered on	**5**	3
Produce regular metrics that clearly state the movement of the industry, the demand for resources and the forecasting of future growth.	Provides career direction for young talent and interested establishments of higher learning whom may want to participate in development of future resources.	5	3



Source: www.metrologycareers.com (ASQ, NCSL, MSC Sponsors)

Workforce Development (continued)

User Training Sources

Currently, the opportunities for 3D Metrology personnel training come from various sources, as listed below. These sources of training are limited both in availability and location, and possibly not scalable to produce the number of qualified 3D Metrology operators required over the next several years to fulfill the needs of our industrial base. This problem is further complicated by the large number of current qualified operators that will retire over the next several years.

1. Equipment OEMs train users as part of a purchase
2. Software companies train users as part of a purchase
3. Metrology service companies train users as part of their operations or through the sale of training services to end user companies
4. Many large companies who maintain 3D Metrology capabilities train their employees. Some of these companies offer apprenticeships or college credit courses.
5. There are several Community Colleges that have course devoted to 3D Metrology. Often, these schools partner with OEMs which donate equipment or software.
6. There are a few major universities that offer degrees or coursework related to 3D Metrology. However, the curriculums are not targeted to future end-users, but to those students that may one day work for an OEM, software provider, Government Standards Laboratory or similar position.

Industry Standards for Operator Training

The Coordinate Metrology Society (CMS) continues its work to develop operator certifications for 3D Metrology Equipment and Software. The organization offers a comprehensive, two-tiered Certification program for metrologists to reach their professional development goals. The portfolio includes a Level-One Certification for 3D portable metrology users that covers foundational theory and best practices. Level-Two Certifications recognize specialized hands-on knowledge used to perform tasks with specific measurement devices. The CMS Level-Two Certification examinations are conducted by CMS-authorized proctors for articulating arm and laser tracker users. Candidates must complete the application process and qualify to take the assessments. The CMS publishes a Certification Handbook, which can be downloaded here.

In 2018, the CMS will also launch two new Certifications designed to recognize critical knowledge and skill sets needed in manufacturing and scientific research. At the 2018 Coordinate Metrology Society Conference, the CMS Certification Committee conducted a pilot assessment for a new CMS Level-Two Certification program for 3D Scanner users. Additionally, the CMS offered a pilot examination for the industry's first Level-One Certification for coordinate measuring machines (CMM) operators. This is the first year the organization expanded beyond their traditional membership of portable metrology users to include CMM professionals, a community that has lacked the opportunity to gain credentials for their specialized expertise in measurement and inspection.

While industry demand continues to drive these efforts, the CMS Certification program has not reached a high level of industry adoption in its infancy years. By 2019, the program will have a complete offering for any user pursuing a career in 3D metrology and working for companies dependent on 3D measurement technologies. The organization has experience steady growth in certified metrologists. The first group of certified metrologists will pursue recertification in 2018, marking five years since the launch of the program.

CMS CERTIFIED

Summary

The PrecisionPath Roadmap has been forged by a team of expert-level consortium members, based on interactive meetings, vertical teams and an industry survey of users focused on portable spatial metrology instruments and supporting technologies. The consortium members have identified the following conclusions for the future of large-scale manufacturing:

Cross-cutting Trends in Portable, Large-Scale Metrology Technologies

Based on data analysis and the industry survey, the PPC team uncovered a variety of trends that cut across multiple 3D measurement technology families. These trends are expected to drive changes in both hardware and software as manufacturers make incremental moves toward Smart Factory initiatives.

1. Wireless and cable-less instruments will become more prevalent as users demand increased flexibility and reduced setup time for measurements.

2. Increasing digitalization of the entire manufacturing enterprise will increase reliance on creation and maintenance of the "digital thread" — linking design to manufacturing to end-use and maintenance. This advancement will create the additional need for 3D metrology systems capable of creating and maintaining the "digital twin" model which documents the "as-built" condition of components and assemblies.

3. The Industrial Internet of Things (IIoT) will become more widespread, and portable metrology systems will be expected to "plug and play" within the larger manufacturing enterprise.

4. Diverse metrology instruments and technologies will be increasingly integrated into larger measurement networks, and will be required to interface for real-time data synthesis.

5. Automation of measurement tasks will increase, and metrology instruments will be able to cooperatively operate within larger automated manufacturing cells without extensive system integration efforts.

Usage Scenarios Also Driving Change

The many use cases reviewed by the PPC revealed that current and emerging trends must be taken into account for the advancement of the large-scale manufacturing industry. Current trends that are expected to continue well into the future include the:

- Elimination of jigs
- Continued push to improve productivity
- Continued push to improve quality of production

Emerging trends in the industry will drive metrology technologies to evolve to address the:

- Additive Manufacturing of Parts
- Flexible Automation including Metrology Systems
- Use of Virtual and Augmented Reality

Photo Credit: Hexagon Manufacturing Intelligence

Summary (continued)

Developing the Future Workforce

From the start of the consortium, the community was very clear about the critical need to build a vibrant and sustainable workforce for the large-scale manufacturing industry. The current workforce is expected to shed nearly 25%, perhaps more, due to retirement in the next five years.

PPC members provided feedback to build the following checklist of actions needed to develop a future workforce:

- Work with the Department of Labor to formally recognize the Metrology Industry. Develop formal job descriptions with standards of education requirements
- Develop a "Survey of the Profession" to get a snapshot of the current workforce. This information would be beneficial to the Department of Labor and companies employing 3D Metrologists
- Work to fund more educational opportunities at Community Colleges
- Engage State Governments to create State MEPS (manufacturing extension partnerships)
- State labor and business development
- State and Federal Apprenticeship councils
- STEM programs
- Engage State and Federal Politicians
- World Metrology Day Promotion
- Generate standards for 3D Metrology Equipment, Software and the Workforce
- Expansion of the Coordinate Metrology Society (CMS) to continue its coordination and certification efforts. Also, work to establish: 1) Industry job descriptions and level of education requirements, and 2) Partner with industry to make certifications standardized and required to work at higher level positions

Roadmap Future Vision Statement

Metrology continues to be a fundamental supporting technology for the manufacture of large-scale components and assemblies in ship-building, aerospace, and other industries. The steady improvement in instrument technology is resulting in faster, more accurate measurements. However it is the synthesis of automation, data management, and interoperability that will leverage these technological improvements to support new, competitive manufacturing paradigms. The workforce of tomorrow will retain the underlying metrological know-how required to perform complex measuring tasks, while understanding the new data-rich environment of digitally-enabled manufacturing.

Photo Credit:
FARO Technologies, Inc.

The Path

The following is a brief history of the PrecisionPath Consortium:

Kick-off Meeting at Coordinate Metrology Society Conference, July 2015
The PrecisionPath Consortium was formally introduced in July 2015 at the 31st annual Coordinate Metrology Society Conference in Hollywood, FL. The organizers, CMS and UNC Charlotte, hosted a kickoff meeting to introduce the industry-driven alliance, its vision and goals, how to participate, and its Roadmap for Innovation. The meeting was well attended by CMSC attendees and leading manufacturing companies, metrology OEMs and more

Working Meeting #1 – Planning and Visioning Council, October 2015
The PrecisionPath Consortium held their Planning and Visioning Council during the Quality Show in late October at the Rosemont Convention Center in Chicago, IL. The first session of the meeting focused on refining the project scope and boundaries. The Council discussed the critical challenges in producing large products to precision tolerances, and then transitioned into identifying metrology technology families used by industry. This segment was followed by the team compiling the most important attributes of these systems for measurement and inspection.

The afternoon session progressed with dynamic group interactions and the use of sophisticated meeting facilitation technology to capture the input. The Consortium took up usage scenarios and amassed data on how portable metrology is being used to support diverse applications across different disciplines. The group proceeded to pinpoint sources of expertise and data for use in the roadmapping process, and firmed up the framing and vision of the PrecisionPath Roadmap project. The organizational structure and operational model were finalized, and the meeting concluded with the election of a Board of Directors and an overview of marketing objectives.

Representatives from many leading manufacturing companies attended the meeting including Siemens, Lockheed Martin, Spirit AeroSystems, Brookhaven National Labs, The Boeing Company. OEMs and metrology service providers also attended the meeting including Automated Precision (API), New River Kinematics (NRK), Hexagon Manufacturing Intelligence, ECM Global Measurement Solutions, Nikon Metrology and Planet Tool and Engineering. Consortium organizers are Ron Hicks, CMS AMTech Chair and UNC Charlotte representatives Ed Morse, John Ziegert, Ram Kumar, and Antonis Stylianou. Other supporting attendees included Tom Lettieri, NIST; Danuta McCall, Facilitate.com; and Belinda Jones, HiTech Marketing.

Working Meeting #2 – Needs and Gap Analysis Workshop, February 2016
The second working meeting of the PrecisionPath Consortium was held February 24 – 25, 2016 at the UNC Charlotte Center City building, 320 E. 9th Street in downtown Charlotte, NC. This well-attended gathering was a continuation of their Planning and Visioning Council meeting held in late October 2015. The team discussed critical production challenges and metrology system attributes, and continued to solidify the framework of the PrecisionPath Roadmap. As the meeting concluded on Thursday afternoon, attendees were able to tour the UNC Charlotte metrology laboratories in the University's Center for Precision Metrology (CPM) and Energy Production and Infrastructure Center (EPIC).

Working Meeting #3 – Steering Council Meeting
The third working meeting of the Consortium was held during the Coordinate Metrology Society Conference from July 25 – 29, 2016 at the Embassy Suites by Hilton in Murfreesboro, TN. During the meeting, several key areas were discussed including the roadmapping process, workforce issues and data management challenges from fusion to interoperability. Team leaders were selected and deliverables were outlined for the October focus group workshop. A brief discussion was held on the early survey results and the need to engage more industry partners and CMSC attendees. The consortium continues to grow and interested metrology professionals from the large-scale manufacturing community are welcome to attend PrecisionPath technical meetings and associated conferences in the next two years.

The Path (continued)

Working Meeting #4 – Technology Innovation Workshop, October 2016
The fourth working meeting of the Consortium was held during the Coordinate Metrology Society Conference from October 26-27, 2016 at the Holiday Inn Charlotte University in Charlotte, NC. During the meeting, the group reviewed differing structures of Roadmaps, and discussed the overall architecture. PrecisionPath team leaders of each working group presented their body of research on technologies, usage/applications, standards, data management, workforce and drivers. An industry-at-large survey of users and managers of portable metrology systems was conducted from May – October 2016 to support the PrecisionPath Technology Roadmapping initiative. A preliminary summary of the Survey results was presented to the group, followed by a brainstorming session for all working groups culminating in concise reports presented to the participants.

Working Meeting #5 – PPC Working Group Meeting, March 2017
The fifth working meeting of the Consortium was held during the Coordinate Metrology Society Conference from March 23, 2017 at the Hyatt Regency in Dallas, TX. PrecisionPath members continued their work to determine and prioritize the technology requirements of industries that manufacture large-scale, high accuracy parts and products. The March program built upon the results of the October 2016 "Technology Innovation Workshop", a continuation of the Planning and Visioning Council forums. Team leaders and members performed a full review of the Consortium's work and prepared a full draft roadmap document for public review. The primary objectives of the meeting was to review output from all working groups and conduct a work session to complete each section.

Working Meeting #6 – PPC Leadership Meeting, July 2017
The group assembled at the CMSC 2017 conference in Snowbird Utah in July 2017. The agenda covered the roadmap status and the future work of the consortium. The attendance at this meeting was evidence that the group should be sustainable following the completion of the initial project.

The results of the industry-wide survey were detailed enough that the roadmap continued to be developed along the lines of its original template. The team at UNC Charlotte has continued to work on summarizing the data, and preparing it in a way that will be easily usable by the individual working groups.

The preparation of the individual sections of the roadmap was somewhat slower than anticipated. All PIs are continuing to synthesize the contributions of the section leaders into a comprehensive draft for review in summer of 2018. This remaining milestone is the primary focus of the group as members seek to complete the initial goals of the project. Work continues on the final editing and formatting of the formal roadmap.

In addition, the leadership team focused on the final presentation materials with suitable graphics and figures to engage the broad spectrum of stakeholders in this project. In other words, this group is locking down on one-page summaries and swim-lane graphics that managers can use to assist in decision making, as well as the detailed supporting material for a more technical audience.

Working Meeting #7 – Roadmap Rollout, July 2018
The group convened at the 2018 CMSC Conference on July 28. A soft launch of the PPC Roadmap was prepared for this target meeting, so members could review and provided feedback on sections of the document. Most importantly, the group is tasked to focus on the Summary section of the Roadmap, and collaborate on this final piece of the effort. The consortium will also reach out to outside experts for additional industry commentary on the final roadmap product. The formal launch of the Roadmap is scheduled for September, just prior to the IMTS 2018, the largest trade show dedicated to the manufacturing industry.

Contributors

NIST AMTech Program Funding

In June 2015, the Coordinate Metrology Society and UNC Charlotte received an Advanced Manufacturing Technology Consortia (AMTech) Grant – Award 70NANB15H068 - from the National Institute of Standards and Technology (NIST), a division of the U.S. Commerce Department. The AMTech Grant is one of 16 awards dedicated to accelerating growth of advanced manufacturing in the United States. The CMS-UNC Charlotte team established the PrecisionPath Consortium for Large-Scale Manufacturing, an industry-driven group working to identify and prioritize the technology needs of the aerospace, defense, energy, and other industries that manufacture large-scale, high accuracy parts and products.

Established in 2013, the NIST AMTech Program reinforces strategic partnerships between U.S. industry, academia and government. The program strives to form new industry-led consortia and strengthen existing ones with the aim of tackling shared technical barriers to the growth of advanced manufacturing. NIST promotes U.S. innovation and industrial competitiveness by advancing measurement science, standards and technology to enhance economic security and improve quality of life. To learn more about NIST, visit www.nist.gov.

The Organizers

The Coordinate Metrology Society and UNC Charlotte share an inspirational vision to solve obstacles hindering U.S. advanced manufacturing. The Coordinate Metrology Society is the one membership organization that connects all of the industry players – end users, OEMs, software developers and service providers – involved in large-scale manufacturing endeavors. Since 1984, the CMS has been dedicated to the advancement of 3D measurement, and caters to metrology users of close-tolerance industrial coordinate measurement systems, software, and peripherals.

UNC Charlotte houses the state-of-the-art Siemens Energy Large Manufacturing Solutions Laboratory located within the University’s Energy Production and Infrastructure Center (EPIC). The laboratory supports collaborations of industry and academia in their research and development of next generation manufacturing technologies. The faculty at UNC Charlotte’s Department of Mechanical Engineering and Engineering Science are experts in precision engineering, motorsports engineering, bioengineering, metrology, computational methods, mechanics and materials. Their engineering programs are nationally recognized.

The PrecisionPath Consortium organizers are:
CMS PrecisionPath Chair: Ron Hicks
UNC Charlotte representatives: Ed Morse, John Ziegert, Ram Kumar, and Antonis Stylianou
Supporting Contributers: Tom Lettieri, NIST; Belinda Jones, HiTech Marketing; Danuta McCall, Facilitate.com

CMS

UNC CHARLOTTE
The WILLIAM STATES LEE COLLEGE *of* ENGINEERING

Contributors (continued)

Board of Directors

Ed Morse – Chair, UNC Charlotte
Ron Hicks – Chair, Coordinate Metrology Society (and Automated Precision, Inc.)
Gary Confalone – ECM – ECM Global Measurement Solutions
Patrick Welch – New River Kinematics (NRK)
Glen Cork – Spirit AeroSystems

Industry Members of the Consortium*

The Boeing Company (Charter Member) – Mons Lee, Ben Rennison, Randy Gruver
BMW – Charlie Rohling
Brookhaven Natl Laboratory (Charter Member) – Matt Ilardo
Caterpillar (Charter Member) – Bill Grant
CMSC – Rina Molari Korgel
CR Onsrud – Tom Onsrud, Patrick Hurst
Lockheed Martin – Bob Elliott, Jay Smith, Chris Barrow
North Carolina MEP (Charter Member) – Kevin Grayson, Phil Mintz
Puget Sound Naval Shipyard – Daniel Hager, Paul Roush
Newport News Shipbuilding (Charter Member) – Joe Sabol, Phil Caudill
Planet Tool & Engineering, Ron Rode
Siemens Energy (Charter Member) – Michael Jones
Spirit AeroSystems – Glen Cork
United Launch Alliance – Forest Kemp

*members affiliated with companies/organizations at the time of project.

OEMs and Metrology Service Providers

Automated Precision (API) (Charter Member) – Ron Hicks, Joe Bioty
Brunson Instrument Company – Richard Powell, Zach Ryan
ECM – ECM Global Measurement Solutions – Gary Confalone
FARO Technologies (Charter Member) – Chris Scholl, Chuck Pfeffer
Hexagon Manufacturing Intelligence (Charter Member) – Joel Martin
New River Kinematics (NRK) – Patrick Welch
Nikon Metrology – Joe Szymanski, Tom Hedges, Eric Brandt
RMR Consulting – Ray Ryan
Verisurf Software, Inc. – Ray Elledge

A Sincere Thank You

to all of the Contributors to this Worthy Project!

Survey Notes

SURVEY NOTES for USAGE SCENARIOS

The written "free-response" input from survey participants regarding different usage scenarios in Section 4 was both enthusiastic and voluminous. For this reason, the responses are captured in this compilation so as not to disrupt the flow of the report. The questions regarding the most positive and negative parts of the experience when performing the tasks involved in the different usage scenarios are listed below, along with the survey responses.

4.1 Calibration

Participants contributed the following text responses on using large-scale portable instruments for Calibration.

When performing this task, what are the easiest parts about it? What do you most enjoy?

- Performing the checks to locate what is out is both enjoyable and simple.
- Setup and task.
- Using trackers over a wireless network to allow greater portability and mobility between the computer, tracker, and measured item.
- Most Enjoyable: Crafting solutions, and ideas/plans on how a part, fixture, or tool can be valued.
- Feasibility and time savings compared to traditional methods.
- Processes are fairly simple and based on the most basic and standard principles. I most enjoy figuring out how something might be calibrated effectively and how to make others able to duplicate the calibration.
- Having Management support to purchase whatever 3D measurement needed to perform my job. The ability to evaluate and correct tooling used as media of inspection.

When performing this task, what are the most frustrating and difficult things you experience?

- Software can be cumbersome and un-intuitive at times. Often, I know a feature or function exists in the software, but struggle to easily/quickly find it.
- Accuracy isn't always available for measurements, usually have to rely on manual "old school" measurement techniques.
- When things are too complex to calibrate simply and other facilities are unable to understand how to repeat calibrations correctly.
- Manufacturing timelines.
- Reporting.
- When systems do not function as they are supposed to.

4.2 Alignment during Assembly

Participants contributed the following text responses on using large-scale portable instruments for Alignment during Assembly.

When performing this task, what are the easiest parts about it? What do you most enjoy?

- Using a programmable system to allow for repetitive measurements to be achieved easily.
- The ability using the technology to verify correct location of components to minimize non-conformance.
- Surface deviation of details. I like to see it come together in live time (Build/inspect).
- The field work.
- Finding and fixing errors that would have caused more trouble later on. It is satisfying to know that you are preventing future problems now when and where the element is assembled.
- Equipment calibration and compensation.

Survey Notes (continued)

- The measurements itself are very easy to perform with the new systems available.
- Creating an alignment plan. Choosing the correct instruments and creating a process to extract the required information with the appropriate levels of accuracy/precision. Determining the correct set of adjustments to ensure the part/assembly meets the requirements.

When performing this task, what are the most frustrating and difficult things you experience?

- Speed.
- Trying to set details that are not perfect to a model that is perfect.
- Reporting.
- Inconsistencies in the verification task. Equipment that is not as repeatable as what is needed.
- Environmental influences in measurement uncertainty.
- The discussions between the different departments to agree on results are somewhat difficult, as there is no common understanding.
- Ensuring that the integrity of the data is satisfactory. Capturing repeatable data.

4.3 Alignment with Machinery

Participants contributed the following text responses on using large-scale portable instruments for Alignment with Machinery.

When performing this task, what are the easiest parts about it? What do you most enjoy?

- Providing real-time feedback to the operator about the quality of the survey.
- Physical issues reaching surface objects with SMR.
- Hardware malfunctions.

When performing this task, what are the most frustrating and difficult things you experience?

- Occasional mis-alignment, or mis-reported data which resulted from poor measurement.
- Simplicity of use. Measured points are exact with no ambiguity as often is the case with photogrammetry.

4.4 In-Process Measurement

Participants contributed the following text responses on using large-scale portable instruments for In-Process Measurement.

When performing this task, what are the easiest parts about it? What do you most enjoy?

- I enjoy the software portion, programming, GD&T and problem solving.
- The software is powerful and allows construction of features to make the task of measurement simple. It also allows the tasks to be saved and re-executed. My favorite part of the current system is the capability to automate inspection with a Robot.
- Automation.
- The problem definition phase. You have to take the Customer's needs and create a plan to address them
- Automation of the process.
- The measurements are the easiest part, the preplanning the most enjoyable.
- The easiest part about it is generating the report with the results at the end of the process. I most enjoy locating subject to its exact location within thousandths of an inch.

Survey Notes (continued)

When performing this task, what are the most frustrating and difficult things you experience?

- Bad GD&T, unclear/unreadable prints.
- When certain constructions are not available in the software.
- Programming automation.
- Late changes or "surprises". Something that upsets the schedule.
- Time to design and implement.
- Delays and unplanned events creating a constantly changing schedule.
- The most frustrating portion of this process for me is either when the equipment has errors or the subject being measured does not wish to comply with the process (does not fit).

4.5 Post-Process Measurement

Participants contributed the following text responses on using large-scale portable instruments for Post-Process Measurement.

When performing this task, what are the easiest parts about it? What do you most enjoy?

- The analysis.
- Enjoy bridging the theoretical to the actual world.
- The programming of the CMM.
- Data analysis in comparison to CAD. Improving quality issues.
- Taking the equipment to the piece and the sense of personal feedback.
- Pre-planning -- Creating programs to complete the inspection.
- The task of measuring is the easiest part of the process.
- Quality and precision. Enjoy the advanced technology used.
- Measuring the actual parts is the easiest part of the process. I enjoy developing a strategy for measuring the parts. From figuring out fixturing methods, to writing the actual inspection routine.
- The portability to take the equipment to the process for verification.
- Customer interaction.
- Tying into the part and measuring the features to the model that are required by engineering.
- Alignment and feature measurements. The part I enjoy the most is being able to measure very complex shapes and provide a clear understanding of the built condition to the design intent.
- The ability to easily and quickly provide value feedback/communication to my downstream customer.
- Quick measurements, measure large-volume with a small machine.
- Knowing that the equipment is appropriate for the task. Being able to provide the customer with valuable information, not just data points.
- Performing the scans and processing scan data (Blue light Structured Scanning).
- Scale bar measurement drift check, learning the software, seeing the data line up with the CAD model
- I enjoy having good, redundant, traceable data from which to analyze.
- Inspecting parts with portable equipment is often quicker and requires much less setup than stationary, permanent alternatives.
- The design of measurement routines with CMM.
- The versatility of the laser tracker system and the ability to determine how the measurement can be performed relatively easily.
- Being able to move around the product. Especially in aerospace. Large parts require the ability to move around freely.
- The collection is usually the easiest part, other than the physical conditions. The analysis is usually more enjoyable due to the challenge.

Survey Notes (continued)

- Setup - programming - ease of use - quickly creating inspection routines - easily generating results in a report format that meshes with office software (word / excel / etc.), i.e. not in a proprietary format. Report must be easy to manipulate.
- My experience is primarily through the eyes of others today, but I will answer this question in past tense. I primarily enjoyed the act of measurement planning. Given the task of inspecting a particular component, I enjoy understanding the failure modes and designing an inspection plan around isolating and measuring those modes.
- The easiest part could span from the actual measurements that are required for the analysis, to the analysis itself! It all depends on the application. I enjoy the challenge in figuring out how to achieve what the customer is required to report/ see; meaning to answer their question "How can we measure this?"
- The most enjoyable part of the process is showing the results of the measurements to the people most affected by survey. I also enjoy determining the best method for making the measurements that will show the true condition of what is being measured.
- I enjoy determining the errors, then finding the adjustments required to fix the part.
- Ease of writing program and quickly acquire data.
- The easiest part is the surveying or inspecting. The multiple ways in which things can be analyzed after the survey inspection is where it all takes place.
- Understanding the build process and trying to eliminate the built-in error in the build process.

When performing this task, what are the most frustrating and difficult things you experience?

- Trying to control the environment and to notice when the assumptions are no longer valid regarding the environment, i.e. when to recalibrate.
- When finding root causes, not always is the obvious solution is the right solution and doable solution.
- Bad GD&T on drawings. Engineers who are unfamiliar with how things are made or measured.
- Sustaining qualified team members to measure and understand data.
- It is too operator dependent.
- Completing the inspection and finding errors in the pre-planning stage. Time constraints to conduct the inspection.
- Helping others understand programming and the data output provided.
- Deciphering a customer's print and communicating with them on what they are looking for out of the inspection or inspection equipment.
- The accuracy is still right on the limits and I am still waiting on tighter accuracy.
- Print to CAD issues.
- Unclear inspection requirements. Bad CAD conversion. Poorly designed tolerances and GD&T.
- Fixturing and correlation.
- Long processing time when working with extremely large volumes of data.
- Manual measurements, repeatability can depend on operator.
- Not having the appropriate equipment. Lack of high accuracy with portable solutions (not up to par with CMMs).
- Reading customers drawings that are poorly laid out.
- Documenting how the job will be done. Getting deliverables (description) from the customer. Waiting on the project to get me in to do my job in a timely fashion.
- Physical obstacles and constraints when measuring.
- Very rarely do portable metrology solutions qualify for use in post process inspection. They generally do not have the accuracy required or they lack the capability to be automated, and a stationary alternative is required (stationary CMM, etc.).

Survey Notes (continued)

- Ensuring that the equipment works correctly, as well as dimension callouts that are not well designed.
- Data uncertainty, data density, setup time, processing time, and analysis of results. By using a laser tracker to measure the panel or reflector surface, we are confined to the ability of the operator to "scrub" the surface accurately. Constantly scanning the surface introduces uneven wear to the SMR. Currently we are exporting raw measured data to a secondary program, then adjusting the coordinate system, then exporting again. It is time consuming and the overall accuracy is defined by the operator's ability to best fit.
- Particularly with the Leica AT the most frustrating thing is line-of-sight limitations.
- Finding an alignment between the measured and nominal data that matches the assumptions of the customer.
- Training underqualified personnel to replicate my tasks - poor direction from engineering / production on design criticalities - poor GD&T on drawings - drawings that do not use design-for-production - drawings that do not use design-for-inspection.
- This answer is very software dependent -- the most frustrating experience I've had is when I've collected a vast quantity of data only to find that the target nest or ADM offset was applied incorrectly. This can be so challenging to correct that sometimes it makes more sense to shoot everything all over again.
- Not having enough information on the project and missing the correct technology to accomplish the given task. Having to wait for a special device to then be shipped to your location costs extra money and time.
- Misinformed customers.
- Trying to find a way to fixture complicated parts to allow access and without deflecting the part.
- Using a portable arm for a high volume of parts. Physically taxing at times.
- Interaction with a customer that does not understand his or her work, and having to in turn own every aspect from start to finish (e.g. holding the customer's hand).

4.6 Reverse Engineering

Participants contributed the following text responses on using large-scale portable instruments for Reverse Engineering.

When performing this task, what are the easiest parts about it? What do you most enjoy?

- Typically we'll use a direct-to-CAD process with articulated CMM arms. The easiest parts to RE are the ones that are machined and can be modeled using geometric features (i.e. planes, cylinders, spheres, etc.) I enjoy being able to break down a part into simple features and then being able to re-create the part in front of me with my modeling software of choice (Creo).
- The easiest part is the scanning itself. Not a lot of thinking required, just focus. I enjoy editing the scan afterwards the most.
- Collecting data and creating the solid model.
- Using Design X.
- Capturing the shape.
- Using Geomagic Design X. Easy to create CAD Models that the customer wants.
- Scanning and data collection.
- Creating CAD files from the surface mesh.
- Converting 3d scan data to a mesh and then to 3d models.
- Reverse Engineering to me is easy when objects can be well defined with point clouds and have clear precise data. I enjoy using new metrology equipment to make the job quicker and more accurate.
- The data gathering and 3-D model generation of various shaped parts. I enjoy doing a variety of different size and complexity of parts.
- Data collection.

Survey Notes (continued)

When performing this task, what are the most frustrating and difficult things you experience?

- The difficulties are usually with cast parts or parts with complex surfaces. These can be difficult to model and using involve a hybrid approach of touch probe and scanning to re-create the part.
- Technical issues are always the most frustrating. When a certain surface will not scan no matter how many times or angles you try.
- Measuring and modeling cast parts that will be manufactured as machined or fabricated parts. What tolerances to apply to the drawing.
- Noisy data sets.
- Creating a CAD model.
- Uneducated customer demanding requirements.
- Post processing of data and generating a NURBS CAD Model.
- Gathering good scan data and post processing the surface mesh to provide an accurate representation of the part.
- Scans of shiny objects (like pipes) are difficult to reverse engineer because the data is noisy.
- When data cannot easily be obtained or when cloud data alignment is out of the specification you need to obtain.
- The more non precise and 3D a part is, makes it a lot harder to model. A cast part must have draft put on the model so it can be manufactured. 3D parts require more time to replicate.
- Limitations of modeling tool.

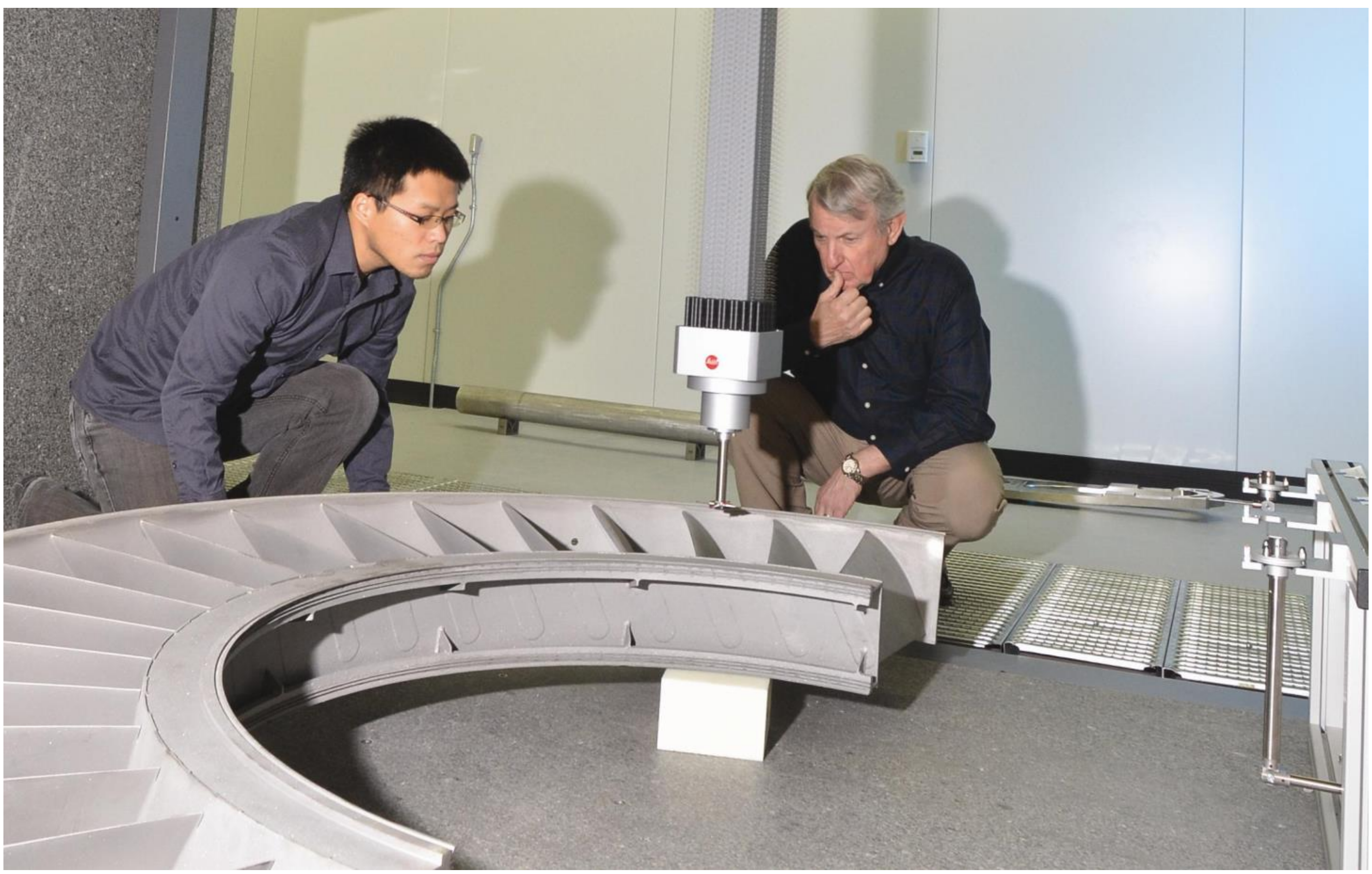


Photo Credit: UNC Charlotte

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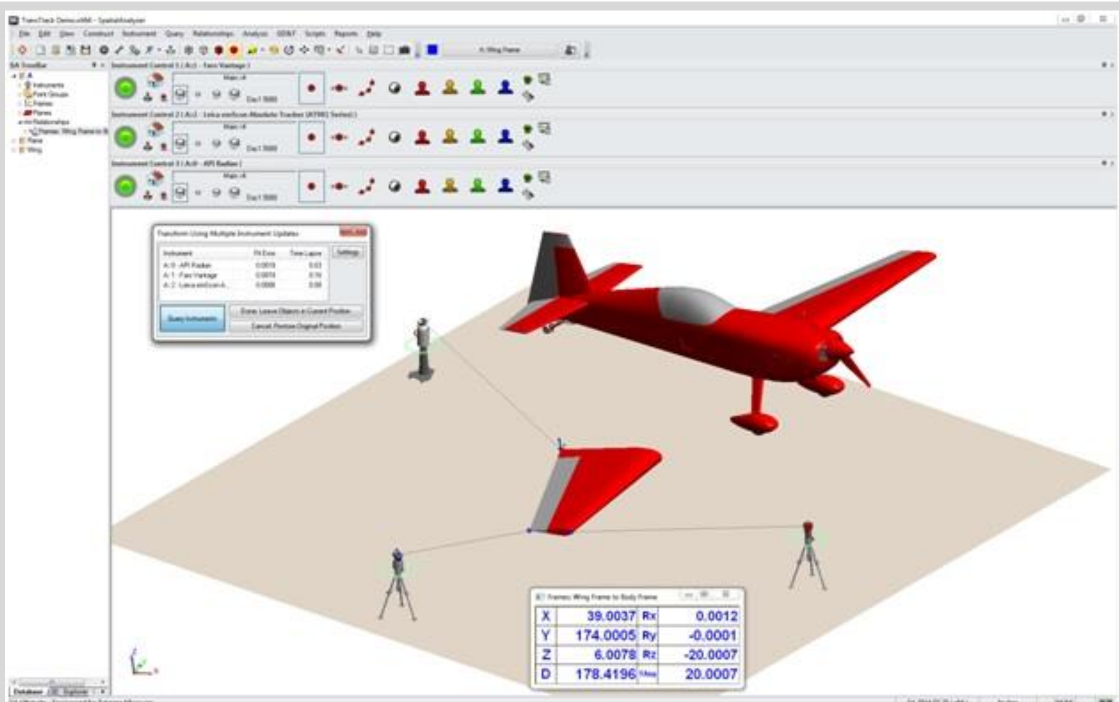

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