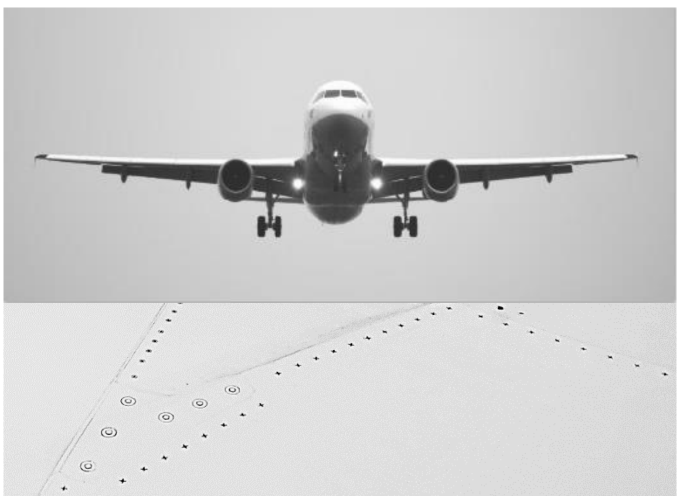
Application Note
for Aerospace Industry

Automated Rivet Hole Inspection and 3D Measurement

with NOVACAMTM Non-Contact 3D Metrology Systems

Evolving needs in aircraft riveting

The high-precision riveting process in aircraft assembly includes drilling, countersinking, and rivet installation. Repeated hundreds of thousands of times on the aircraft body, every step in this process contributes to the structural integrity of the aircraft and to minimizing unnecessary aerodynamic drag. This is why strict tolerances apply to the geometry and surface quality of rivet holes, countersinks, and installed rivet head flushness.



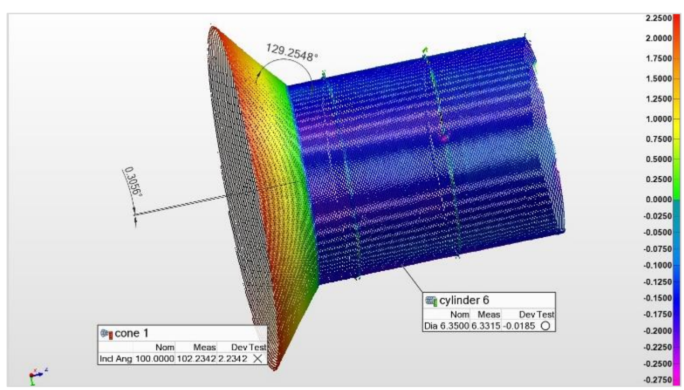
But while aircraft riveting has become mostly automated and robotized, quality control (QC) of the process is still often limited to coupon inspection in assembly plant labs. Fortunately, changing to high-precision 3D automated inspection is now an option that offers much improved understanding of the fastener installation process and significant cost savings.

Automating rivet inspection

In support of the industry's transition to 100% automated and data-driven QC of riveting, NOVACAM systems for riveting inspection offer speed, precision, and facility for integration with robots. The systems' scanning probes measure rivet holes, countersinks, and installed rivet heads right during the assembly process, on the plant floor. They provide automated non-contact micron-precision measurements of dimensional and surface quality parameters, enabling full traceability and improving QC of both intermediate and final results of the riveting process.

NOVACAM SYSTEM PARAMETERS
for FAST NON-CONTACT 3D MEASUREMENTS
of FASTENING PROCESSES

- *Measure rivet hole & countersink IDs from 4 to 30 mm*
- *360^{o} coverage without shadows*
- *Micron-level measurement precision*
- *Up to 100,000 3D point measurements per second*
- *Ability to measure aspects including:*
  - ✓ *3D geometry and GD&T parameters: inside diameter, cylindricity, countersink included angle, concentricity of rivet hole and countersink, perpendicularity of hole to surface, etc.*
  - ✓ *Defects such as cracks and burrs*
  - ✓ *Roughness*
  - ✓ *Rifling caused by tool chatter*
  - ✓ *Flushness of installed rivet head*
  - ✓ *Straight and tapered fastener holes*
  - ✓ *Metal alloy and composite (CFRP) surfaces*



Rivet hole and countersink angle measurements

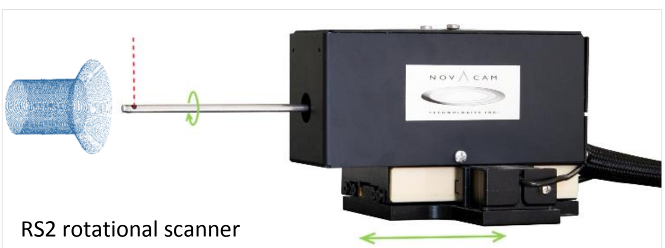
3 systems for rivet measurement

To suit the wide variety of measurement needs in the riveting process, Novacam offers a choice of 3 systems for non-contact measurements:

system	Measures		
	rivet hole ID	countersink	rivet head
BOREINSPECT™	✓	✓	
SURFACEINSPECT™		✓	✓
RIVETINSPECT™	✓	✓	✓

All three systems are based on low-coherence interferometry technology and use an interferometer (NOVACAM MICROCAM™-3D/4D) to produce and process light signals. The three systems differ in their fiber-based scanning probes:

1. The **BOREINSPECT system** uses a **rotational scanner** (RS) to reach inside rivet holes with a small-diameter rotational probe.



RS2 rotational scanner

2. The **SURFACEINSPECT system** uses a **galvo scanner** to scan the rivet hole area from above in a raster manner.

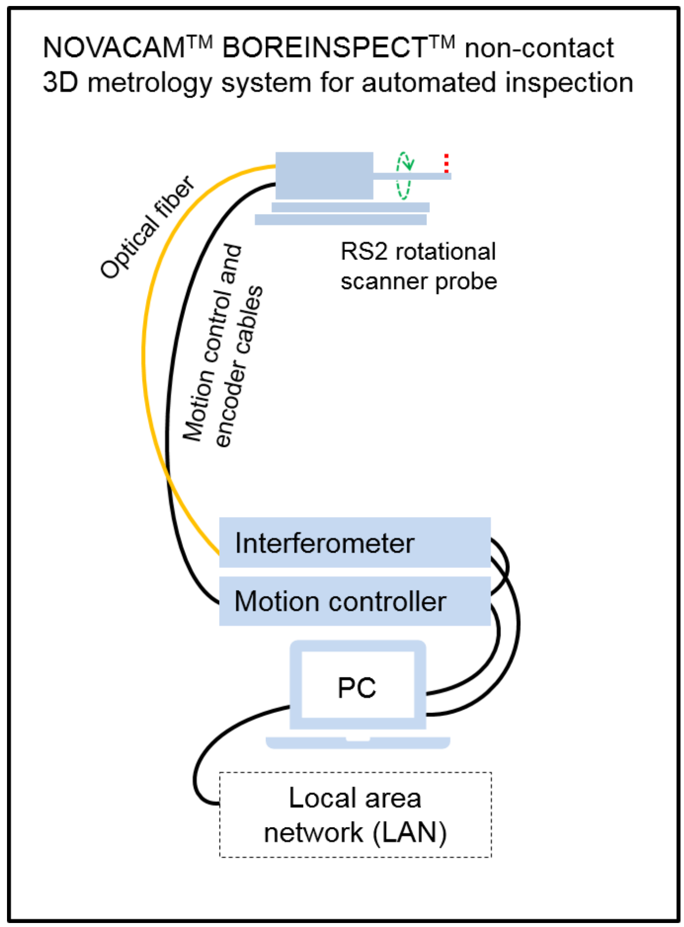
GS1 galvo scanner

3. The **RIVETINSPECT system** uses both the **galvo scanner and the RS** to provide full coverage of the riveting process.

Facility for robot integration

NOVACAM rivet measuring systems are all fiber-based and modular, meaning that the scanning probes are connected to the signal-processing interferometer with an optical fiber. The probes can be installed wherever required in the process—on a CNC, robot head, or any combination of precision stages—while the interferometer (4U 19-inch rackable unit) may be located several meters away, such as on the base of a robot.

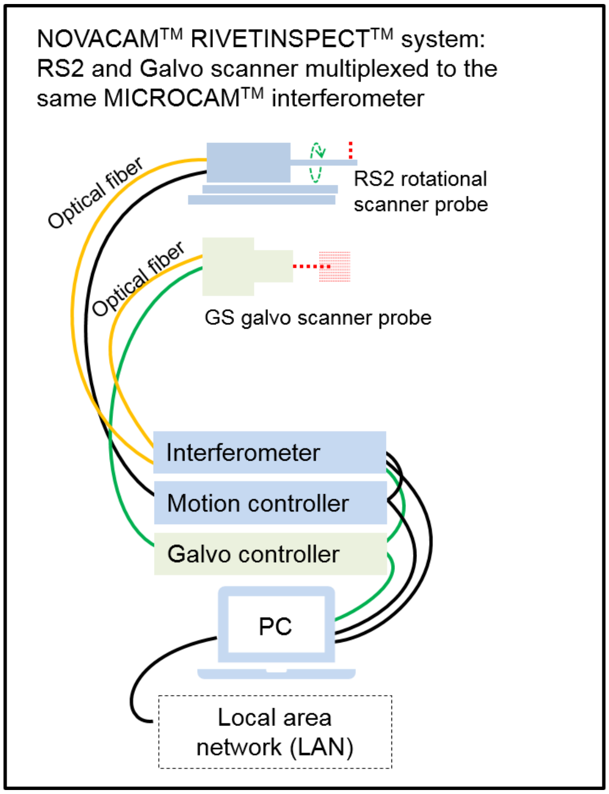
A simplified diagram of the BOREINSPECT system configuration for integration on a robot arm is shown here below.



Simplified diagram of the BOREINSPECT system, where the RS is set up as robot end-effector (not to scale)

The configuration for the SURFACEINSPECT system is similar to the above, with the galvo scanner substituted for the RS.

Below is a simplified diagram of the RIVETINSPECT system configuration for integration on a robot arm. In this setup, both probes (the galvo scanner and the rotational scanner) are multiplexed with a single interferometer, with one probe scanning at a time.

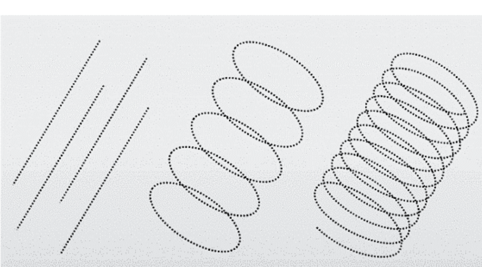


Simplified diagram of the RIVETINSPECT system where both the RS and GS are set up as robot end-effectors (not to scale)

Acquired 3D measurements

NOVACAM 3D metrology systems acquire surfaces in a point-by-point manner. Light is directed onto the surface, and reflected light signals are captured and processed.

The user selects the scan path. With the BOREINSPECT system for example, scan paths may be linear, circular, or spiral.

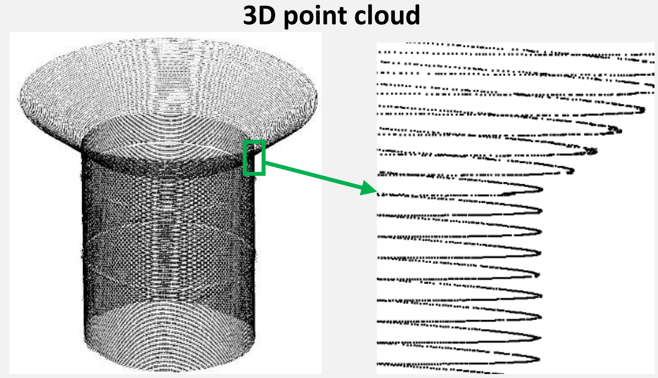


With the SURFACEINSPECT system, the light beam traverses the lens field of view (FOV) rapidly and following a raster pattern.

From each scan, the systems simultaneously generate three sets of raw data: 1) a 3D point cloud (micron-precision measurements),
2) a light intensity map, and 3) a height map.

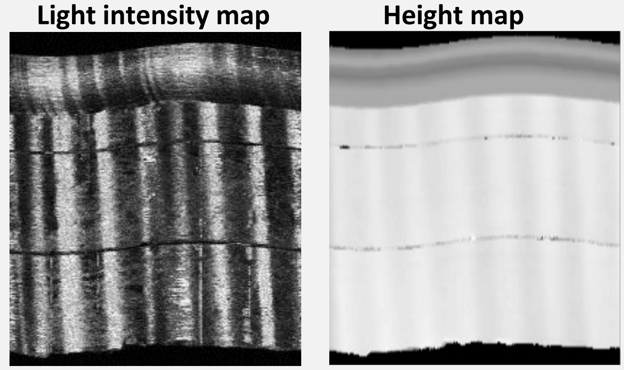
Below is an example of data acquired from a spiral scan of a 6.35 mm (¼') diameter rivet hole using the BOREINSPECT system.

3D point cloud



This high-density 3D point cloud comprises over **947,000 3D measurement points**. With the system scan rate of 100,000 Hz, probe rotation speed set to 20/sec, and a spiral pitch of 50 µm (~2,000 µin.), measurements were 4 µm (~157 µin.) apart, giving 4,987 3D measurements per rotation. Scan time was 9.5 seconds.

Light intensity map **Height map**



These data sets are generated at the same time as the 3D point cloud file. They represent an unwrapped view of the rivet hole ID and may reveal evidence of defects such as chatter (seen as vertical stripes) and inter-laminar defects.

The 3D point cloud is useful for both interactive and automated 3D analysis of the measured surface and for calculating 3D GD&T parameters.

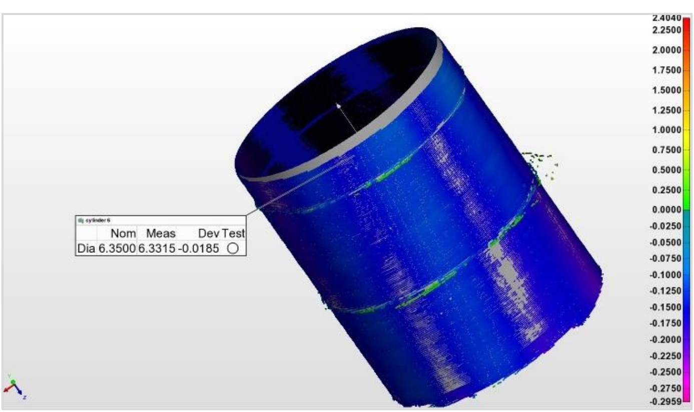
The light intensity map and the height map facilitate defect detection and measurement. More on this later.

Options for point cloud analysis

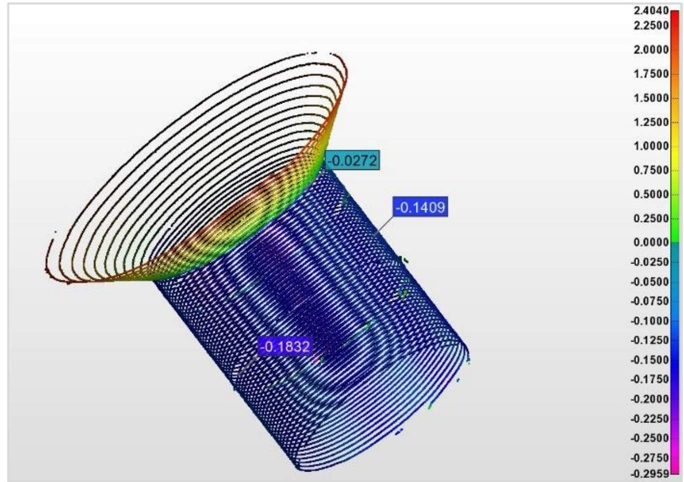
The generated 3D point cloud may be analyzed interactively or automatically using CAD/GD&T (computer aided design/geometric dimensioning and tolerancing) software. Novacam offers **PolyWorks Inspector™**, an industry-standard 3rd party CAD/GD&T software, as an option with its 3D metrology systems. The software provides powerful capabilities for evaluating the 3D point cloud with respect to user-defined criteria (rivet hole ID feature nominals and tolerances) or a reference CAD model.

PolyWorks Inspector offers both interactive 3D visualization and analysis, and **fully automated analysis and go-no-go reporting.** Users may define their own macro-based rivet inspection reports, such as the one shown on page 9 of this document. With automated rivet inspection reports, no operator input is required.

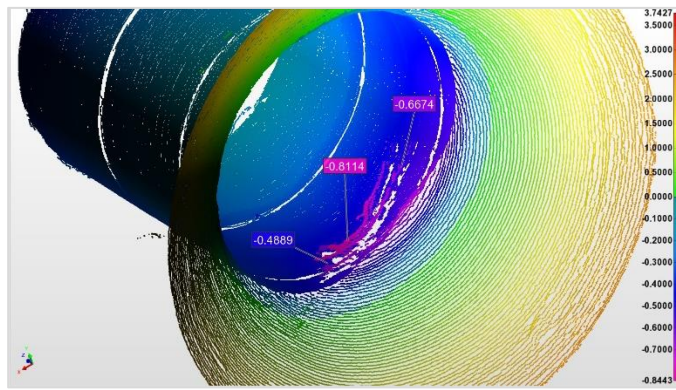
Below are examples of 3D data visualization in PolyWorks Inspector. Views such as deviation maps help bring users key insight into the drill-and-fill riveting processes.



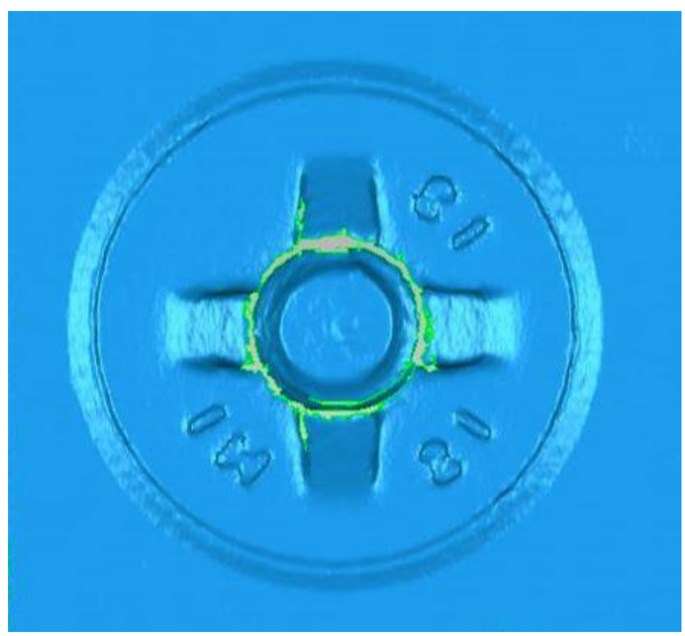
Rivet hole shown as 3D deviation map from cylinder. Users can zoom or pan around the point cloud image, as well as query measurements of features or individual points.



Rivet hole and countersink shown as 3D deviation map from a cylinder.



Rivet hole and countersink shown as 3D deviation map from cylinder. A burr defect (pink) is evident on the rivet hole ID.

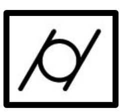

Installed rivet head measured with the SURFACEINSPECT system and viewed as an STL file in InnovMetric PolyWorks Inspector.

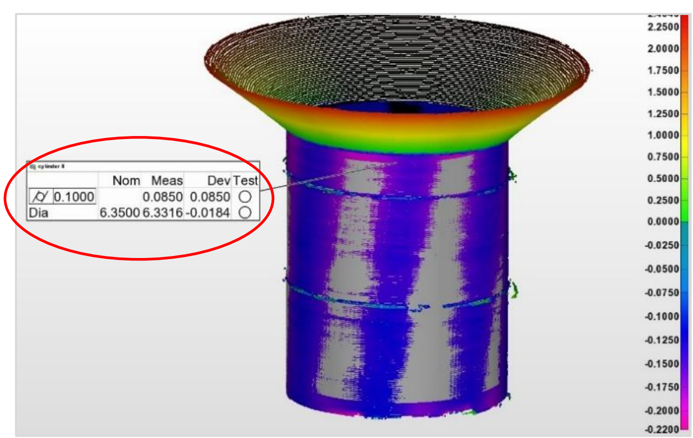
3-dimensional and GD&T measurements

Below are examples of riveting process measurements that may be obtained with NOVACAM systems. Red ovals outline the named measurement.

Length (grip length, etc.)

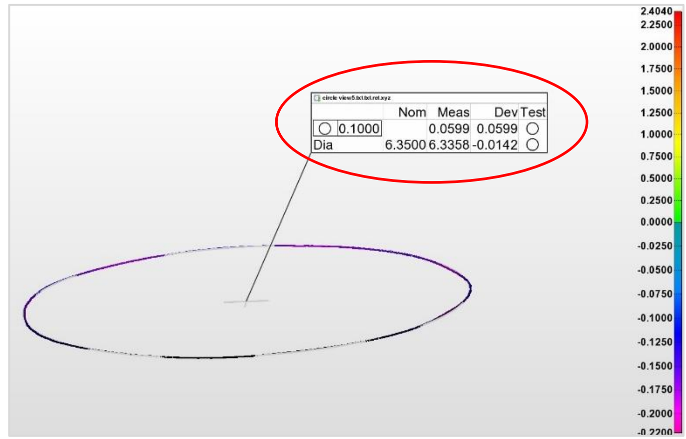
Diameter and cylindricity



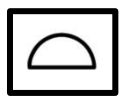


Roundness (Circularity)

Roundness is affected by defects such as rifling (i.e., chatter that may, for example, be caused by incorrect drill feed rate) or ovality (from uneven entry and exit of the drill bit).

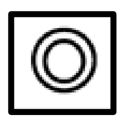


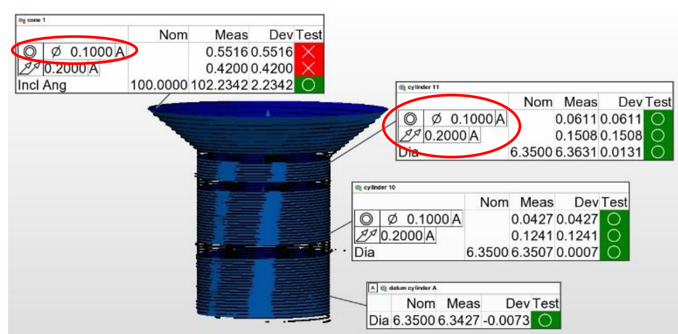
Profile – conicity, taper, etc.



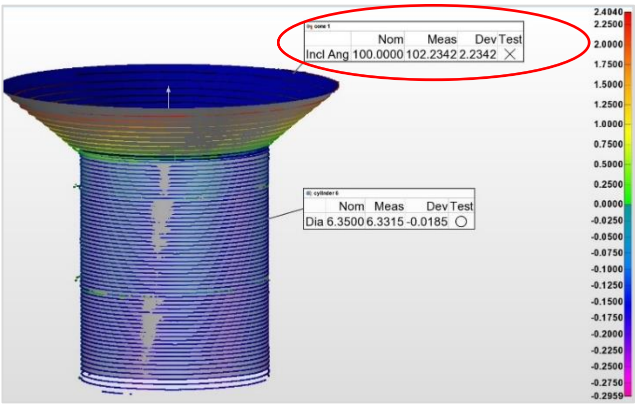
Cone and taper tolerancing, as well as other types of profile tolerancing, are supported through PolyWorks Inspector functionality.

Concentricity



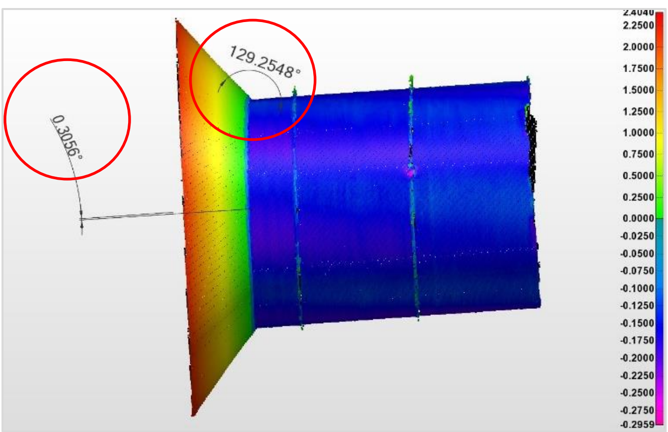


Countersink included angle



Other angles

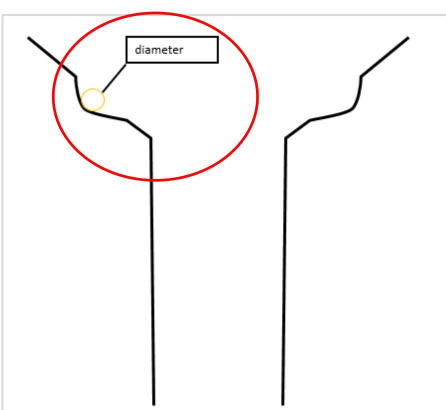
Angle between rivet hole and countersink axes & angle between countersink and rivet hole



Perpendicularity of rivet hole axis to surface plane

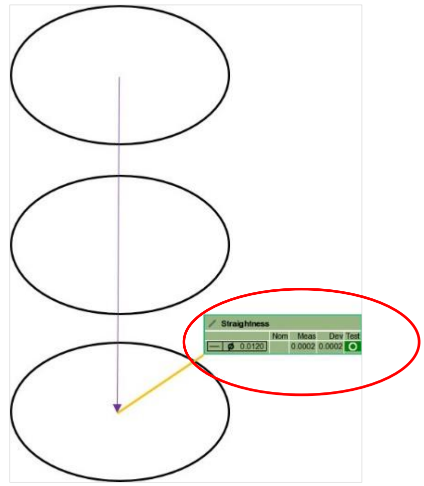
Given the surface reference plane datum, the perpendicularity of the bore and/or countersink axis to this datum may be calculated.

Radius of ID grooves



Axial straightness

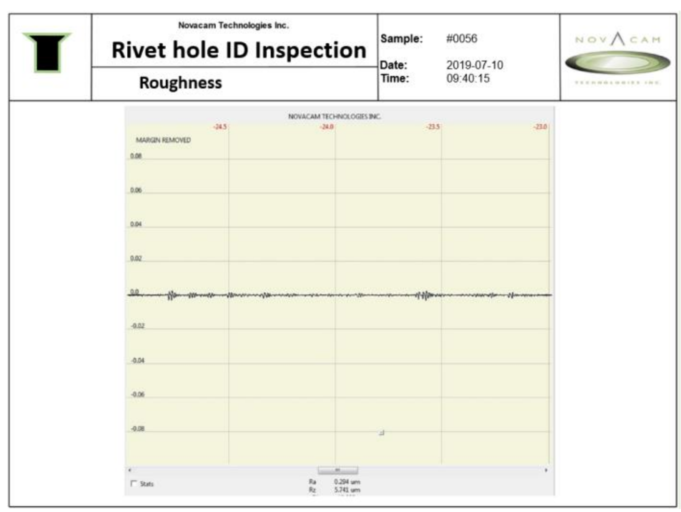
Axial straightness of the rivet hole may be calculated from three or more circular profiles or from a high-density spiral scan of the hole ID.



Roughness measurement

Depending on system configuration, the roughness profile of a selected section of the rivet hole is available directly from NOVACAM acquisition software and may be included as part of an automatically generated rivet hole inspection report.

Roughness measurements may be obtained from both linear and circular scan paths.



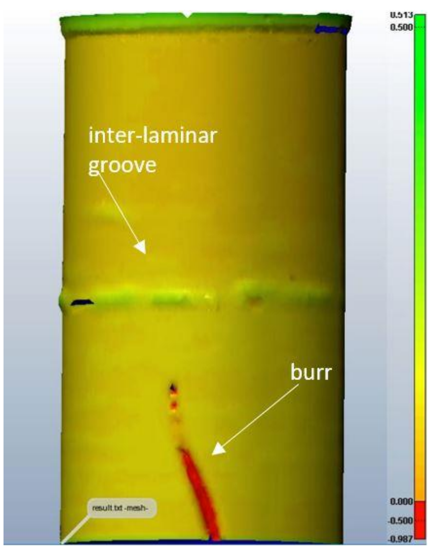
Defect inspection & measurement

Using 3D point cloud

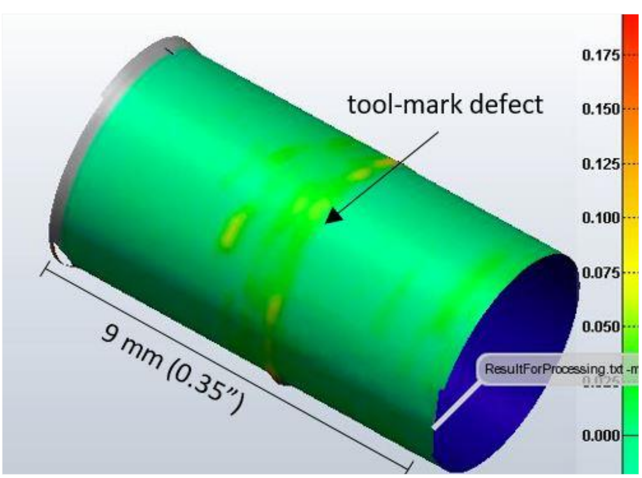
High density 3D scans of rivet holes allow for thorough inspection and measurement of riveting process defects. Common defects include:

- Surface cracks
- Inter-laminar defects such as gaps or offsets
- Burr debris
- Gaps caused by tearing of composite materials
- Tool mark defects, or
- Rifling (chatter) defects.

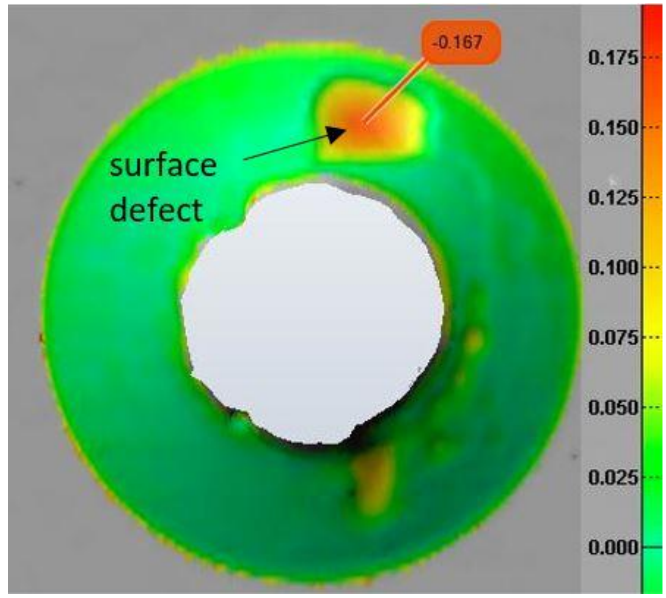
Below are examples of defects that may be inspected and measured with NOVACAM systems in conjunction with PolyWorks Inspector GD&T analysis software.



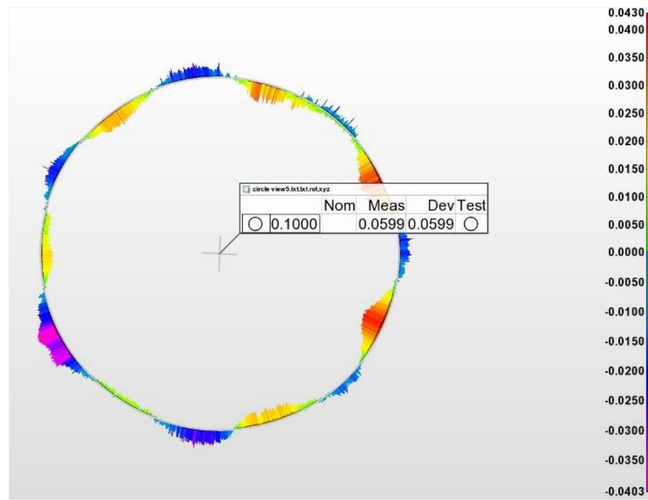
Rivet hole ID with an inter-laminar groove and a burr (STL view)



Tool-mark defects at the interface of material layers (STL view)



Countersink with a dent (STL view, scale in mm)



Drill bit chatter on a circular profile of the rivet hole

The 3D point cloud may be:

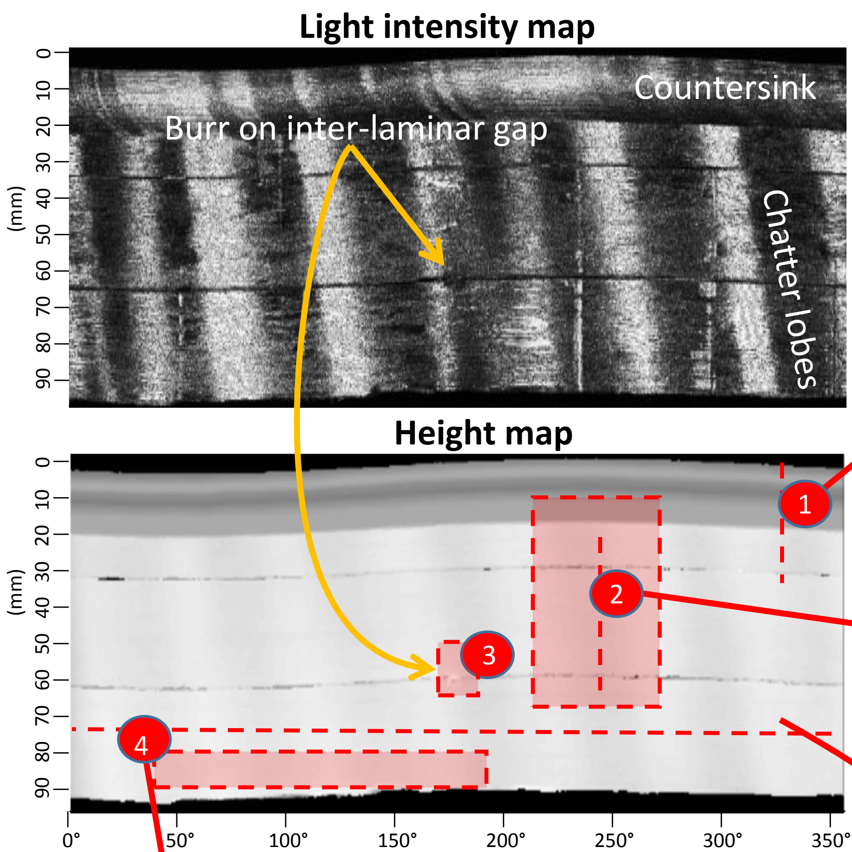
- Viewed interactively to examine and measure defect patterns and/or
- Analyzed programmatically to detect defects of specified sizes and shapes.

Mitigation procedures in case of defects may include testing the drilling procedure on a coupon or changing a drill bit.

Defect inspection & measurement

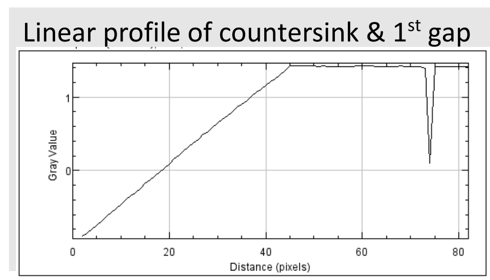
Using height maps and light intensity maps

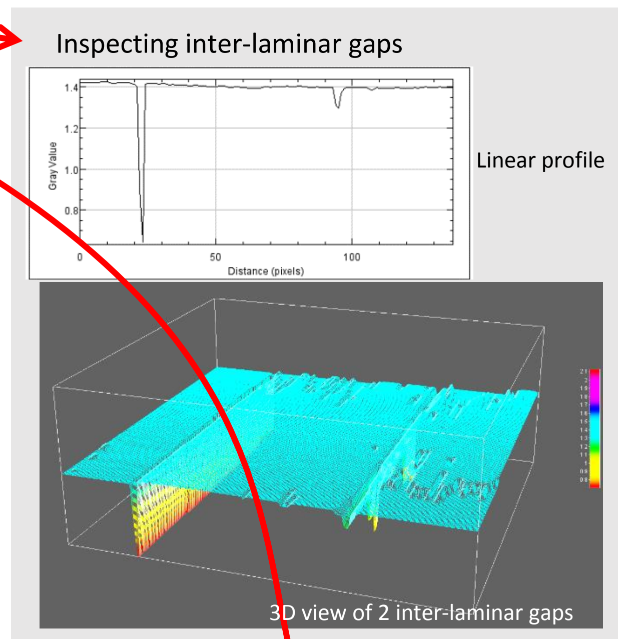
With NOVACAM 3D metrology systems, defect detection and reporting can be completely automated. Nevertheless, for clients who want to also look for defects interactively, the height and light intensity maps generated in addition to 3D point clouds are excellent tools, especially for bore ID defect detection and analysis. The following maps represent an unfolded ID surface of a 6.35 mm diameter drilled rivet hole. The hole is 9.5 mm deep.

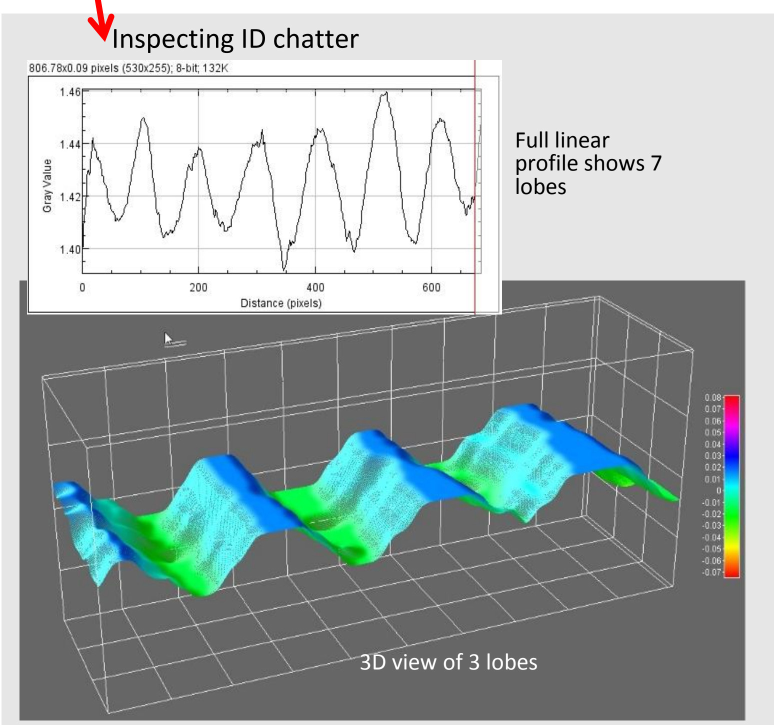


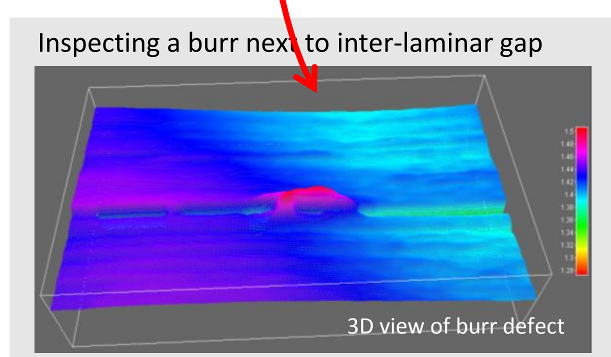
The **light intensity map** is equivalent to a borescope image or a photo obtained by a vision system: it is a useful visual reference but does not contain height data.

The **height map** provides micron-precision height values of the surface - as seen below.









Full support for automation

NOVACAM acquisition software allows users to automate the full rivet measurement cycle, including scanning, data analysis, and subsequent reporting. To automate these repetitive tasks, users configure Scan Definitions, which comprise measurement sequences and subsequent reporting.

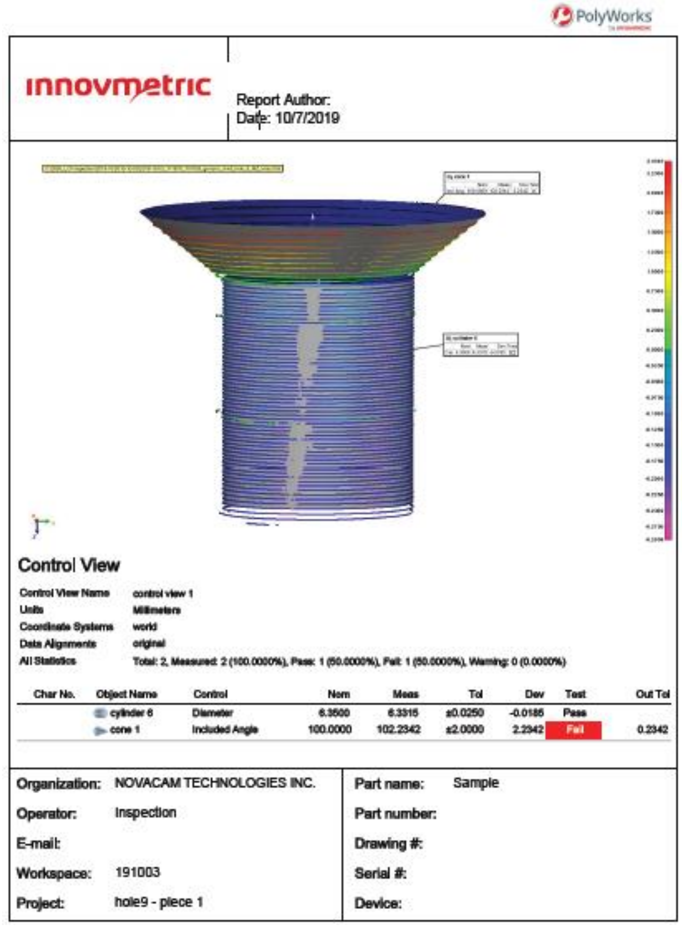
Typically, Scan Definitions are predefined to enable measurements corresponding to engineering drawing callouts. Once a Scan Definition for a particular rivet geometry is created, it can be named and saved for subsequent use.

Scan Definition are invoked automatically by a PLC- programmable logic controller or by an operator with the push of a button. In this way, the inspection cycle and the measurements obtained are independent of the operator.

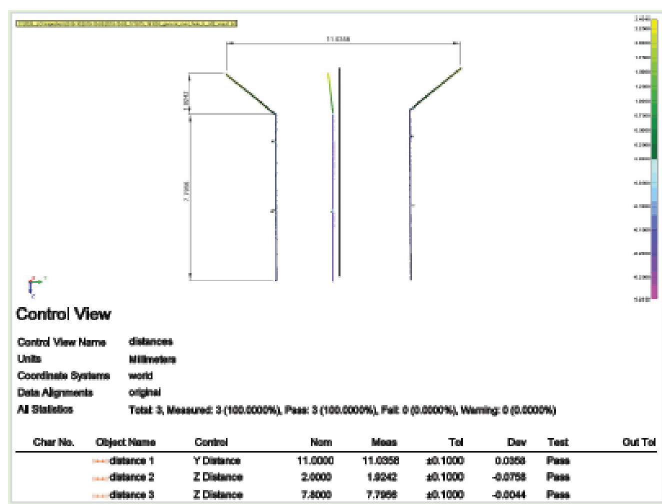
Example of automated rivet report generated with PolyWorks Inspector™

Configuring automated rivet hole measurement reports with PolyWorks Inspector involves specifying nominal and tolerance values for each feature of interest.

Below is an example of such an automated go-no-go report for specific rivet hole dimensions. The first page shows that while the rivet hole passes the diameter control criteria, the countersink fails on the countersink angle criteria. The second report page shows that countersink height and diameter measurements are within tolerance, as is the height of the rivet hole.



Page 1



Page 2

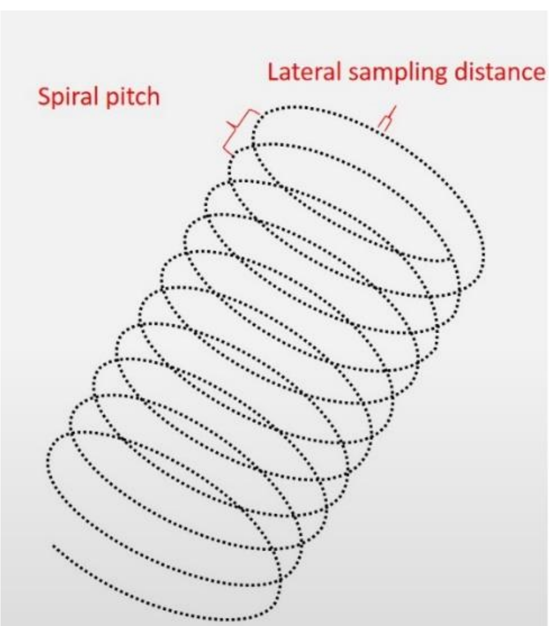
System resistant to important environmental factors

NOVACAM systems are not affected by ambient lighting, air perturbation, or industrial floor environment, which makes them suitable for plant-floor deployment as well as lab environments. Nevertheless, the scanned surface should be cleaned of cutting fluid using an air knife.

Measurement speed and density beyond CMMs & other gauges

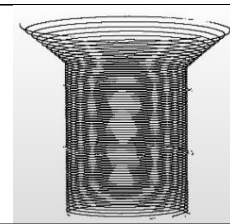
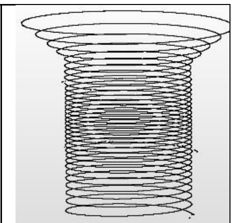
Since NOVACAM systems with MICROCAM-4D obtain 100,000 3D point measurements per second, the generated 3D point clouds are orders-of-magnitude denser than point clouds obtained with CMMs or other commonly used high-precision instruments. A typical rivet hole takes 1 to 9 seconds to scan, with the cycle length depending on the grip length, the features measured (e.g., rivet hole only or also the installed rivet head), and the required density of 3D data points.

With the BOREINSPECT system, the density of the scan may be adjusted by adjusting the spiral pitch (see diagram below).



By selecting a very small spiral pitch (e.g., 0.05 mm), the user obtains the highest density point cloud, such as the point cloud shown on page 3. Notably, such large density and quantity of data are not always necessary; for example, to save extra seconds in in-process inspection, a sparser spiral scan typically provides more than sufficient basis for high-speed ID assessment.

The table here below shows two examples of sparser scans, the time they take and the amount of 3D data they provide.

		
Rotation speed	20 rotations/sec	20 rotations/sec
Spiral pitch	0.2 mm	0.4mm
Lateral sampling distance	4 µm	4 µm
# of points per rotation	4,987	4,987
Total # of points	236,896	118,448
Scan time	2.4 seconds	1.2 seconds

Alternative options for processing 3D data

For clients who prefer to process the raw 3D scan data themselves using their own display and analysis software, a range of raw data options are available: 3D point cloud, height map, light intensity map, STL file, and more.

Input for statistical process control

NOVACAM systems offers the option to provide measurement data to riveting process control programs and to SPC (statistical process control) monitoring of the riveting process.

Which system is best for me – BOREINSPECT, SURFACEINSPECT or RIVETINSPECT system?

The choice of the system depends on your measurement needs. The following table compares the three NOVACAM rivet measuring systems.

System	RIVETINSPECT™ system	
	BOREINSPECT™ system	**SURFACEINSPECT™ system**
Benefits		
Measures rivet hole ID	YES	
Measures countersink	YES	YES
Measures rivet head (post installation)		YES
Unique advantages	✓ Ability to scan IDs of a range of sizes with the same probe	✓ Raster scanning is the fastest area acquisition available without moving stages.
Common Characteristics		
Technology	Low-coherence interferometry (LCI)	
Type of measurement	Non-contact, optical, collinear measurements (enabling even the measurement of high-aspect-ratio features such as angled surfaces, undercuts, etc.)	
Environmental considerations	Resistant to air perturbation, ambient lighting and to cutting the beam	
Light wavelength	1,310 nm, infrared	
Light bandwidth	Broadband light	
Pointer for alignment purposes	In-probe red laser @ 650 nm	
Instrument safety[1]	Class 1M laser product: < 20 mW of infrared, < 5 mW of in-probe laser pointer	
Acquisition speed	2,100 to 100,000 3D point measurements per second, depending on interferometer model selected (MICROCAM-3D or MICROCAM-4D)	
Light spot size	Variable, typically 13 to 22 µm (512 to 870 µin.)	
Key differences		
Key differentiator	Measures rivet hole ID with a rotational scanner. • Makes up to 30 rotations per second • Acquires up to 100,000 3D points / second • Sampling steps along rotational path and in axial direction are user configurable.	Acquires surfaces in raster manner with a galvo scanner. • Acquires up to 50,000 3D points / second • Sampling steps are user configurable.
Customization options	Standard rotational probe models are available with diameters ranging from 0.55 to 4.6 mm. Standoff options include fixed or adjustable (see BOREINSPECT system product sheet).	Standard galvo head models are available with field of view ranging from 4.7x4.7 mm to 84x84 mm (see SURFACEINSPECT system product sheet)
Deployment considerations		
Maximums	Standard stack thickness up to 100 mm.[2]	Galvo field of view standard up to 84x84 mm
Probe positioning	Probe should be within (±) 0.5 mm of bore centerline to capture the entirety of ID features.	Galvo head is positioned over surface of interest, within (±) 0.5 mm of the galvo lens standoff distance.
Approximate probe weight	1.2 kg (2.5 lb) (including standard 4.6 mm probe)	Weight of galvo head without lens: 650 g (1.4 lb) in case of GS1 or 1,900 g (4.2 lb) in case of GS2.

System	RIVETINSPECT™ system	
	BOREINSPECT™ system	SURFACEINSPECT™ system
Deployment considerations cont.		
Approximate probe size (depth x width x height)	170 x 64 x 76 mm (without probe)	Size of galvo head without lens: 79 x 69 x 78 mm (in case of GS1) or 114 x 97 x 94 mm (in case of GS2)
Minimum bending fiber radius	50 mm	
Fiber length	Up to 10 m from probe to interferometer	
Max cable length to motion controller	10 m to motion controller	10 m to galvo controller

[1] Class 1M laser product: Visible and invisible laser radiation. Do not stare into beam or view directly with optical instruments.

[2] Non-standard rivet hole IDs, lengths, and inclusion angles can be accommodated with custom setups. A trade-off exists between probe diameter (which affects rigidity) and probe length. For longer probes, centralizers may be required.

Selecting a system for your riveting inspection needs

QC inspection requirements for riveting vary from plant to plant, and from rivet type to rivet type. To select the most appropriate system for your needs and to maximize the return on investment (ROI) for your company, Novacam recommends the following 5 planning steps:

1) Identify your base measurement requirements

While a wide range of measurements is available with NOVACAM 3D metrology systems, identifying requirements specific to your application is the first step.

These requirements may, for example, include:

- **Dimensional measurements** – e.g. rivet hole ID, length, straightness, included angle of countersink, rivet hole angularity (from perpendicular), or flushness of the installed rivet head.
- **Roughness measurements** - inside the rivet hole and/or countersink.

2) Define what defects must be detected

For each rivet inspection application, the expected types of defects depend on the materials being joined (aluminum or titanium alloys, CFRP, steel, etc.) and on the mechanisms and tools used in the process. Defects may, for example, include **inter-laminar defects, burrs, or chatter.**

The next step therefore is to define:

- **The types of defects** that are inherent to your materials and process
- **The shapes and sizes of defects** that should be detected automatically.

3) Estimate your inspection cycle time limits

As stated earlier, with NOVACAM 3D metrology systems, a typical rivet hole inspection cycle takes several seconds. The cycle time will of course partly depend on the measurements required. For example, measurements of roughness and small size defects require higher data density scans (and therefore slightly slower scans) than scans done strictly for dimensional measurements.

In lab environments, an inspection cycle of a few seconds per coupon hole is generally acceptable. However, for in-process (plant floor) inspection, shaving each second off the cycle counts. We support clients in calculating the time demands corresponding to your particular measurement requirements, and in striking the right balance between your inspection cycle limits and measurement requirements.

4) Plan to leverage your 3D data to improve your processes

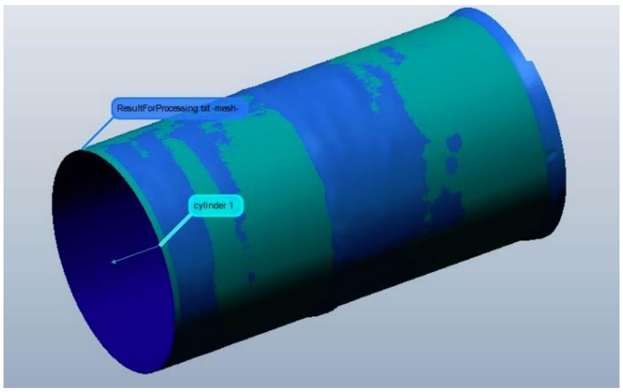
When clients are considering upgrading from physical measurement tools such as test pin gauges, the much larger amount of data and measurements available with NOVACAM systems may seem overwhelming. In 1 to 5 seconds, a point cloud of 100,000 to 500,000 3D points is generated – that's a lot of data! Perhaps not surprisingly, some clients worry that with more numerous and precise inspection criteria, too many rivet holes previously considered compliant may start failing inspection; their first reflex may be to use the new technology to simply replicate old familiar data sets, such as pass/fail based only on rivet hole ID. However, this would be a missed opportunity.

In fact, with well-planned inspection criteria and data analysis, clients come to appreciate the value of the large 3D data sets: this data offers the **ability to quantify a range of key process parameters, to track trends, and to ultimately gain new insight into the fastening process**. Process insight leads to **process improvement**, and process improvement leads to fast return on investment.

5) Plan to realize operational savings while improving quality

First, since NOVACAM optical probes are non-contact, they do not wear out, and therefore are not consumable; no money or time needs to be spent in replacing or recalibrating them.

Second, there are savings to be made on our client's drill-and-fill consumables. For example, given the cost of consumable drill bits and the cost of the drill-bit replacement process, **it makes sense to replace drill bits only once their efficacy has measurably deteriorated**. To establish drill bit wear, the measured 3D geometry of each rivet hole may be automatically compared with the specification shape of the rivet hole (see image below).



Colour-coded image of dimensional difference between the rivet-hole specification (green) and the measured rivet hole (blue)

As the drill tool wears out, the hole ID will gradually decrease. Trending the dimensional change of consecutive holes can determine the optimal time to replace a cutter while staying within tolerances. With such smart approach to drill bit replacement, clients achieve operational savings – cutting down on work stoppages and on budgets allocated for drill bits.

Conclusion

Today aircraft and automotive manufacturers seek to improve their processes through multiple approaches - automation, robotization, as well as tracking and analyzing detailed 3D measurement data. Since human safety is ultimately at stake, 100% 3D inspection of the fastening process is the new expectation and increasingly the norm.

By deploying NOVACAM systems to provide in-process high-precision 3D riveting process measurements, assembly plants are able to:

- Decrease their rivet inspection cycle time
- Detect out-of-tolerance parameters early
- Decrease scrap and rework
- Optimize consumables usage, and
- Achieve overall savings.

Novacam encourages technicians and engineers in charge of riveting processes to contact us to discuss your application and particular challenges.

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