Advances in 3D Video Borescope Measurement Technologies for Defect Characterization

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Abstract

Advances in structured light and stereo based 3D measurement technologies are transforming video borescopes from pure visual inspection tools to data-based inspection and measurement equipment. New technologies allow the characterization of cracks, pits, dents and corrosion in process piping, boiler tubes, steam headers and rotating equipment to a level of accuracy that was previously only possible through destructive testing and measurement. However skilled application of these measurement technologies is critical to attaining accurate measurements and actionable data. When using traditional 2D data sets to perform measurement, errors can easily occur without the inspector even being aware. New measurement technologies allow the use of a 3D point-cloud to check measurement set up in real-time from multiple angles and perspectives, which greatly reduces the error potential and increases confidence. The underlying principles of 3D borescopic measurement will be discussed, as well as examples of measurement set-up and defect characterization in aircraft engine and power generation applications.

Introduction

With the measurement technologies available today, remote visual inspection (RVI) is complimenting or, in some cases, replacing other non-destructive testing (NDT) methods. In the past, inspectors could identify potential flaws or cracks and capture images, but now advanced video borescopes can measure, map and analyze these indications in a three-dimensional (3D) format, and also share images and data wirelessly with remote experts.

Traditional methods, such as stereo and shadow measurement, have a greater potential for inaccuracies. When an inspector works with a two-dimensional (2D) image, there often isn’t enough detail or depth to ensure the cursor is set correctly. In contrast, 3D measurement technologies allow the real-time use of a 3D point-cloud to check measurement setup and
ensure accuracy of cursor placement. This ability to check work and deliver exact measurements is not only critical for RVI inspection, but also to train employees and entrust inspection tasks to less experienced inspectors.

The emergence of video borescopes equipped with 3D measurement technology has transformed RVI inspection and helped transition knowledge and skill-sets to the next generation.

**Improving inspection efficiency and accuracy with 3D visualization**

Most inspections start with a general visual assessment, or general inspection, looking for indications such as dents, pitting or coating loss, that require quantitative assessment. In the past, measurement optical tips were limited in terms of brightness, depth of field, or field of view and not suitable for general inspection. This led to inefficient workflows where, upon finding an indication using a non-measurement optical tip, the probe was withdrawn, a measurement tip was attached, and the inspector would try to navigate back to the indication to perform a measurement. The process was then reversed to continue the general inspection. In addition to being inefficient, often the indication couldn't be found a second time for measurement.

Traditional borescope-measurement means capturing a 2D image using a measurement tip, then positioning cursors on that image to perform the measurement. With 3D technologies, the borescope system computes 3D coordinates at the cursor positions to perform the measurement calculations. The accuracy of these 3D coordinates is affected by many factors including object distance, viewing angle, glare, noise, and brightness. In addition, surface contours, viewing perspective, shadowing, and surface discolouration can lead to improper cursor placement due to misinterpretation of the viewed scene. For example, the measured depth of a dent at the root of a blade can be drastically affected by the cursor placement due to the curvature of the surface, which is difficult to assess from a 2D image. These limitations can lead to costly, unnecessary engine removals or the continued operation of assets with out-of-limits indications.

Therefore it is critical to mitigate these risks with 3D point-cloud visualization, and inspectors are now transitioning to borescope technologies that provide this capability. Two such technologies available today are 3D Phase Measurement (3DPM) and 3D Stereo Measurement (3DST).
3D Phase Measurement Technology

3D Phase Measurement combines bright, full-screen viewing optics for general inspection with on-demand measurement upon finding an indication. This streamlines the inspection process by reducing or eliminating probe withdrawals for tip changes and ensures than indications found during the general inspection are quantitatively assessed with precision.

Known as ‘phase shifting’, 3DPM uses a triangulation technique, well known in optical metrology. Detachable 3DPM optical tips use a miniaturized LED-based system to project a series of shifted line patterns (Fig 2) onto the viewed surface. Images of these patterns are captured and processed to compute a full 3D map of the surface.

3D Stereo Measurement (3DST)

Just like 2D Stereo Measurement, 3DST utilizes stereo optics to match two views of a surface from slightly different perspectives. 3DST employs more advanced calibration and processing algorithms to compute a 3D coordinate for every matched pixel prior to the start of the measurement process resulting in a full 3D surface map. It generates a full 3D point-cloud representation of the target surface that can be viewed, manipulated, and analyzed (Fig. 3)
The 3D surface maps produced by 3DPM and 3DST allow the system to display a 3D point-cloud visualization, or point-cloud view, of the 3D data that underlies the computed measurements along with the cursor locations on the 3D surface. This allows the inspector to make several critical accuracy checks that are difficult or impossible to make using the 2D image alone. These assessments include:

- **Noise level**: Indications such as small pits, dents, and grooves where serviceable limits can be as small as 0.003” in depth, pushing the capabilities of borescopic measurement systems. It’s very difficult for inspectors to determine from a 2D image whether the system is actually resolving the depth of the feature or if the measured depth is the result of noise in the data. The 3D point-cloud view allows the inspector to see whether the feature is well resolved or hidden in data noise.

- **Deepest point**: When measuring the depth of a feature, it’s important to ensure that the measurement is taken at the deepest point. A selectable 3D depth-map view colours the point-cloud data according to its distance from the depth-measurement reference plane. This allows the inspector to ensure that a cursor has been properly placed at the deepest point on the feature.

- **Reference-plane accuracy**: Accurate measurement of features, such as engine blade tip curl, tip clearance, root dents, and platform offsets, relies on establishing an accurate reference plane. Surface curvature or data noise can cause the reference plane to be tilted or offset, yielding inaccurate results. The 3D point-cloud view includes a reference-plane border that ensures the reference plane is aligned with the reference surface.

- **Data quality**: Glare, reflections, and surface finish can all cause areas of localized inaccurate data. The 3D point-cloud view reveals these issues so that cursors can be moved away from them or the image can be re-captured if needed.

- **Cursor placement**: When measuring on a discontinuous surface, such as the edge of a blade, an inspector may think he has placed a cursor at the edge of one surface when
the coordinate is actually on another surface adjacent to the edge in the 2D image. This can result in large measurement errors that may not be obvious when viewing the 2D image. With 3D measurement inspectors can check their cursor placement in 3D to avoid errors.

When selecting measurement technology to use in a given application, there are several factors to consider. Due to its high-quality imaging and measurement on demand capability, 3DPM is preferred in most applications where a 6.1mm diameter probe can be used and surfaces are not too reflective. Applications requiring a 4.0mm or 8.4mm probe or those that involve highly-reflective surfaces are better served by 3DST. 3DST can also be used for defect measurement in Fluorescence Penetrant Inspection under UV illumination.

![Fig 4: 3D Stereo Measurement on surface with florescence penetrant.](image)

Together, 3DPM and 3DST are complementary solutions that bring the benefits of advanced 3D point-cloud visualization to a wide range of inspection applications.

![Fig. 5: A 3D point-cloud helps inspectors identify and measure the true depth of an indication at its deepest point.](image)
Accuracy of 3D Measurement Technologies

Both 3D measurement technologies achieve a high degree of accuracy. The measurement accuracy curves below were created from trained third party test results using 3DPM on a GE Video Borescope (Mentor Visual iQ Videoprobe) under controlled conditions with a matte finish test block. They should be interpreted as system capability under ideal conditions. Actual results vary with application, surface conditions, equipment condition, and user expertise.

Fig. 6: Accuracy curve for length measurement of a crack

Fig. 7: Accuracy curve for depth measurement of a pit or dent

Study of 3D Stereo Measurement accuracy is underway and expected to have similar performance.
Boosting confidence

In the aviation industry, the costs associated with an incorrect serviceability decision, whether it’s grounding a plane, pulling an engine unnecessarily or allowing a plane to fly with an out-of-limits condition, can be enormous. These costs and risks drive the need for technologies to improve decision-making accuracy while minimizing downtime.

Many serviceability decisions are based on borescopic measurements, so 3D point-cloud visualization technology allows inspectors to avoid many of the common pitfalls of traditional measurement approaches by letting them see the quality of the 3D data. This gives inspectors more confidence in their data, and asset owners more confidence in the serviceability decision. Advanced 3D visual inspection technology is not only solving a major challenge regarding the aging workforce and talent gap, it’s helping inspectors do their jobs better and make more informed, accurate decisions while reducing unnecessary downtime. While inspections are only one component in aviation maintenance and repair, inspection technology advances are dramatically improving aviation operations and keeping aircraft in the air longer.

Other industries like Power Generation and Oil & Gas are also benefitted with borescopic 3D measurement technology. For O&G, an important application is the measurement of Pipelines and manifold structures welding. 3D Phase Measurement can quantify the weld features such as root penetration, undercut mis-alignment (Hi-Lo) and provide a manipulation of weld root profile (Fig 8, Fig 9 and Fig 10).

![Figure 8: 3D scan and profile measurement of a weld bead (left)](image1)
![Figure 9: Cross-section profile view of the same weld bead; note the curvature (center)](image2)
![Figure 10: Point-cloud view of the weld bead and the surrounding part (right)](image3)
Recent and Future Development

With powerful computing hardware and intelligent algorithm, 3D measurement technologies will allow more automated measurement and defect detection. New functions have been derived for specific applications such as Blade Tip Clearance Measurement. By selecting location of engine blade tip, software will calculate the minimum, maximum and average tip clearance of the defined edge.

For corrosion, pitting or build-up measurement, 3D measurement technologies can measure a defined area with 4 points, and then provide minimum, maximum and average depths or heights. It will reduce the inspection and measurement time and accurately locate critical area of for further evaluation.

Optics development will allow 3D Phase Measurement for further and closer surface scanning. It will allow the technology for larger area scanning and metrological measurement. 3D point-cloud can be converted to CAD model data. For reverse engineering of critical parts, borescopic 3D measurement technology will provide the internal surface profile that cannot be obtained by general scanning equipment. Borescopic 3D measurement technology is at it early stage, there will be more developments and applications coming out that might even beyond the NDT or inspection domain.