Advances in Three Dimensional Measurement in Remote Visual Inspection

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Abstract
Recent developments in industrial video borescope technology have enabled three-dimensional surface scanning of equipment internal spaces. Named 3D Phase Measurement, the optical metrology technique of structured light and optical phase shifting has been adapted to the size restrictions of a six millimeter diameter video borescope, to allow the 3D visualisation benefits to be transferred to Remote Visual Inspection (RVI). By combining this projection system with high-quality viewing optics and sophisticated, proprietary processing algorithms, it is now possible to view a full 3D map, or point cloud, of the inspected surface, which is used in conjunction with measurement to obtain more precise information about an indication.

Keywords: Remote Visual Inspection (RVI), 3D, video borescope, structured light, phase shifting, 3D phase measurement, point cloud.

1. Introduction
Remote Visual Inspection (RVI) is a long-established inspection and non-destructive testing technique. Highly capable video borescopes are deployed for RVI applications where an indication must be quantified or measured. They find application throughout aerospace, power generation, industrial and process applications and are used frequently in turbine inspections to quantify defects and help determine fitness-for-operation. Video borescopes are used during periodic maintenance routines, as well as by original equipment manufacturers during initial manufacturing. They can be used to inspect for leaks, corrosion and surface cracking, and to check internal gaps, identify the reasons for blockages, and detect and remove foreign objects. With such a wide range of potential cost-saving and productivity-enhancing uses and requirements, it is logical that video borescopes have developed considerably over recent years.

2. Borescope Development
In its most basic form, an RVI system consists of a lens and illuminating light source, connected to a light transmitting extension, which ends in a viewing eyepiece. Designs have now progressed somewhat from these very basic endoscopes. Today, fiber optics or distal LEDs are the illumination mechanisms used, while the human eye has been very much superseded by CCD or CMOS video devices. At the same time, there have also been significant improvements in the functionality of video borescopes with the introduction of on-board computing power. Added computing capability has enabled the development of several methods for defect quantification or absolute measurement

3. Quantify Asset Condition
The measurement of flaws, discrepancies and clearances is as important as their detection and identification. Prior to the development of 3D Phase Measurement by General
Electric’s Inspection Technologies’ business, there have been three major measurement systems: comparison, stereo, and shadow measurement.

Comparison measurement is based on a known reference dimension in the inspection image, which is used to measure other objects in the same view and plane. (The reference object may also be set in place by the instrument manufacturer or introduced with the probe.) Comparison measurement accuracy depends on two factors: the distance from the distal end of the borescope to the object, and the degree to which the object plane is perpendicular to the borescope camera.

![Figure 1: Diagram of a comparison measurement in a video borescope probe.](image1.png)

Stereo measurement uses a prism or dual lens to split images, allowing the camera to capture left and right views with a precise angle of separation. The position of user-place cursors is then analyzed using a computer algorithm and triangulation geometry is applied to obtain accurate measurements. The accuracy of stereo measurement systems depends on the separation distance between the prism or dual lens, on the sharpness and contrast of the image, and on the distance from the distal end of the borescope and the object being measured. Stereo measurement does not depend on perpendicularity between the object plane and the video borescope distal tap.

![Figure 2: Typical borescope stereo measurement.](image2.png)
Shadow measurement relies on a shadow triangulation of tip-to-target distance. A shadow measurement tip projects a shadow across an inspection image. The position of the shadow in the image is related to the distance from the tip to the object. With this information, the shadow measurement system can accurately calculate the size of user-selected features or defects. Shadow measurement accuracy depends on the distance from the distal end of the borescope to the object. Image sharpness and contrast is less important. The object plane must be perpendicular for some types of measurement and may be skewed for other types of measurements.

![Diagram of a shadow measurement and corresponding image](image)

**Figure 3:** Diagram of a shadow measurement and corresponding image

### 4. 3D Phase Measurement

Even with the current range of qualification techniques, accurate measurement is a difficult aspect of using video borescopes. Operators must be highly trained and practiced to obtain reliable and repeatable results. This expertise level has been addressed as RVI is now further-professionalized as an official NDT discipline and is a module within ASNT’s TC1A Level-I, II, and III qualification, testing, and certification process. In addition to operator skill level, the limitations of each technology mentioned previously affect measurement results.

With the development of 3D Phase Measurement, significant improvements have been made in system accuracy, repeatability, measurement range, and ease-of-use when carrying out measurement tasks, as will be documented below.

3D Phase Measurement is based on an existing optical metrology technique known as optical phase shifting. This generally involves sequentially projecting three or more structured light patterns onto a surface, capturing on camera an image of each pattern on the surface and then processing the pattern images to produce a 3D map of the surface. Accuracy depends on the distance from the distal end of the borescope to the object plane. The object plane may be skewed without affecting accuracy. Increased accuracy over stereo measurement systems is derived from a doubling of the separation distance of the structured light projection system as compared to the separation distance of dual-imaging optics.
With 3D Phase Measurement, the video borescope projects sinusoidal shadow patterns onto the surface. These patterns are then analyzed using specific algorithms and a 3D surface map is generated from the X, Y and Z coordinates of the created point cloud. Shown below in Figure 5 are a general diagram and a photograph of a 3D Phase Measurement optical tip.

Unlike comparison, stereo or shadow measurement systems that operate on a point-by-point basis, 3D Phase Measurement processes the image data to generate a full 3D map of the viewed surface before beginning the measurement process itself. The user can then simply place measurement cursors on a normal, full-screen image without marking a reference dimension, matching stereo points, or shadow identification steps that can be challenging and time-consuming with other measurement techniques.
Phase Measurement imagery also provides a great deal of information about an indication. For example, with a dent, the operator can perform an initial depth measurement by placing two cursors outside the area of the dent to establish a reference plane then view a cross-section of the surface passing across the dent. If the point cloud is then viewed, the system will indicate the location of the measurement cursors, focus on the region around the measurement and can optionally color code this region, using a depth scale relative to the reference plane. This can assist in more precise measurement by indicating whether or not the cursors are appropriately placed around the dent and serve as a methodology validation.
The versatility of Phase Measurement imagery is also demonstrated by the fact that the 3D map can also be rotated, zoomed and viewed to provide further information on the shape of a defect and the location of the measurement cursors.

Figure 8: 3D scan and profile measurement of a weld bead (left)
Figure 9: Cross-section profile view of the same weld bead; note the curvature (center)
Figure 10: Point cloud view of the weld bead and the surrounding part (right)

5. **Features for Increased Productivity**

The 3D Phase Measurement system relies on the fitting of a patented, precision, miniature light projection system into a detachable optical tip. One major advantage of this is that the same video probe can be used both to view and to measure. This offers significant productivity benefits, as using stereo and shadow can be time-consuming as well as requiring expertise. For example, with stereo measurement, it is first necessary to spot the defect using a non-measuring optical tip. This tip must then be replaced with a stereo tip, the defect must be re-located, the image is frozen, the cursors are matched and the measurement is taken. With 3D Phase Measurement, the defect is located, the image is frozen and measurement is carried out. There is no need to change the tip, increasing overall productivity.
6. Important, Immediate Applications

An important application of the new technology is the measurement of aircraft engine tip-to-shroud clearance. Aircraft engines, and other axial-flow turbo machinery, are typically designed to minimize the radial gaps between the blade tips and the blade housing or shroud. Gaps between tips and shrouds can reduce efficiency by allowing gas or air to leak into the downstream stages. Consequently, it is very important to check this clearance, both during manufacture and also during service as the gap changes during engine operation. High operational rotating speeds and high temperatures can cause radial elastic growth of blades, as well as thermal expansion of the shroud.

Historically, one method of measuring tip-to-shroud clearance has involved inserting a thin metal rod into an axially drilled bolt and attaching this assembly to the fan case so that the end of the rod is positioned where the blade tips should be. After the engine has been operated, the amount of wear on the rod is measured. Obviously, this is not a high-accuracy technique and its execution often generates problems such as the liberation of metal from the rod, which can cause damage to the engine. Phase measurement now offers a simple, non-contact and high-accuracy technique for measuring tip-to-shroud clearance.

7. Conclusions

3D Phase Measurement is a fundamentally different approach to defect measurement characterization and a significant breakthrough for video borescope technology. Never before has 3D surface scanning of small internal spaces been possible. The complete system offers increased accuracy, increased productivity, measurement technique validation for the operator, and considerably more information about a surface or indication.