SURFACE DAMAGE EVALUATION OF FLAT HONEYCOMB COMPOSITE AIRCRAFT PANELS USING 3D SCANNING TECHNOLOGY

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ABSTRACT

Current techniques for the quantitative measurement of surface damage on honeycomb composite aircraft panels are often performed by hand and subject to interpretation or variation based on inspection personnel. They are also costly due to the time required to perform these assessments. Recent progress has revealed the potential for 3D scanning technology to be used as a measurement tool for dented aircraft panels. This type of procedure is common in manufacturing settings and is beginning to see implementation within inspection routines for commercial and military aircraft. This paper presents a method for the inspection of approximately flat honeycomb composite panels. Laser scanning is first performed on a dented panel surface to produce a point cloud of 3D scan data. A CAD surface is then fit to the point cloud data to approximate the original, undented surface of the panel. The distance between the 3D scan data and surface fit is obtained using an automated deviation analysis tool to quantify dent depth and size. This method supports the extraction of surface contour information with measurements shown to be within 0.1 mm of those taken via Vernier caliper and coordinate measurement machine. As a result, this technique has the potential to support timely extraction of surface dent measurements during on-site component analyses.

1 INTRODUCTION

1.1 3D scanning

3D laser scanning is a method that may be used to collect shape and contouring data based on real-world objects. A point cloud of geometric data is usually developed by means of optical technology, which corresponds to the surface of the scanned object, or subject. This data can then be extrapolated to form a rendering of the subject. In the last few decades, these systems have become increasingly important for quality control in the manufacturing industry [1]. Today, they play a key role in the inspection of complex assemblies in many mechanical fields, such as aeronautics and automotive.

A common method of 3D scanning is based on triangulation, which uses laser light to probe an environment. These systems, such as FARO® ScanArm technology, involve shining laser light on a subject while exploiting a camera to look for the location of the laser dot. This technique is called triangulation because the laser dot, camera, and laser emitter form a triangle, wherefrom known lengths and angles determine the geometry of the triangle, in turn providing the location of the laser dot. This 3D scanning mechanism is the basis for the method described in this paper.

1.2 3D scanning applications

There are many examples of 3D scanning being used to digitize real-world objects for engineering and scientific applications. A typical application is the measurement of roughness and waviness, as well as the gauging of 3D topology of machined surfaces [2]. 3D scanning has similarly been used to characterize drilling tools, whose geometry makes their analysis challenging [1]. During inspection processes in manufacturing engineering, the surfaces of common mechanical parts may be measured via 3D scanning and compared to corresponding CAD models [3]. This applies to the aerospace and medical industries, wherein even the smallest defects may be unacceptable and thus require identification [4]. CREAFORM provides a 3D scanning-based NDT solution, which is marketed for pipeline damage inspection, as well as the assessment of hail damage on aircrafts. 3D scanning has also proved promising for automated control and robotics applications [5].

The use of 3D scanning technologies has likewise extended beyond the mechanical field for which they were originally intended, examples of which are thoroughly investigated in [2]. Cultural heritage is a common field as explored in [6-9]. A similar application has involved the digitization of large, fragile statues under non-laboratory conditions [10, 11]. In human engineering, 3D scanning has been used to extract and compile anthropometric data pertaining to apparel sizing, protection equipment design, and workstation layout [12].

3D scanning represents advancement from traditional coordinate measurement machine (CMM)-based methods in common inspection processes. One reason is its non-invasive nature, which is attractive compared to CMM systems that require probe-to-specimen contact during inspection. Provision of reference data for CMM-based systems may also be challenging, requiring physical alignment of each inspection piece. However, both systems may be controlled manually or via computer.

1.3 Inspection requirements for aerospace honeycomb composite panels

Honeycomb composite structures are used extensively in commercial and military aircraft. Examples include floor and cover panels, which support the weight of transport personnel and cargo, as well as cover and protect underlying structures. Surface damage is often measured manually via depth gauge or ruler. A disadvantage of this approach is that measurements are subject to interpretation or variation based on inspection personnel. Inspections are performed periodically to characterize the presence and nature of surface damage, including sharp and smooth dents, which may be identified via marking (as shown in Figure 1). Measurements may also be repeated by additional inspection personnel to confirm observations. The status of a panel is determined based on dent limit definitions defined in the standard repair manual of an aircraft. These limits are defined in terms of collective dent depth and length measurements made on the panel. Exceeding these limits may lead to damage propagation and subsequent failure of the component.

Figure 1. Dent cluster on a retired aircraft panel with dent impressions marked by inspection personnel

1.4 3D scanning method for honeycomb panels

In most manufacturing and inspection processes, 3D scanning is employed to compare point cloud data to known CAD information about a subject. In terms of aircraft panels, however, the original geometry cannot be determined once the surface has been deformed via denting. As a result, this study shows how the original surface geometry of a panel can be approximated using point cloud data from the damaged part. This supports subsequent quantification of the deviation between the original and damaged geometries, resulting in a measurement of dent depth. This method is promising due to the need for quick, reliable manners of determining surface damage dimensions on aerospace components. It is likewise attractive due to the potential for application in any field requiring surface damage evaluation. Furthermore, it represents an automated inspection solution, which may be used to replace manual processes.

2 DAMAGE QUANTIFICATION OF FLAT PANELS

2.1 Materials

Flat panel damage was quantified based on two retired aircraft panels with properties as listed in Table 1.

Property	Value
Top face sheet material	Al 7075-T6
Core material	Al 5052
Bottom face sheet material	Epoxy/fiberglass
Adhesive	Heat-resistant epoxy Hysol® EA 934NA
Total panel thickness	12.7 mm (0.50”)
Top face sheet thickness	0.51 mm (0.020”)
Core thickness	11.7 mm (0.46”)
Cell size	3.2 mm (0.125”)
Cell wall thickness	0.025 mm (0.001”)

Table 1. Aircraft panel specifications

2.2 Methods

3D scan data is gathered manually by a FARO® ScanArm laser scanning apparatus mounted to a lab workstation, producing a 3D point cloud representative of the deformed surface of the aircraft panel. The results of this process are as illustrated in Figure 2. Scanning is performed in conjunction with Geomagic Design X software, which supports handling of the data.

A CAD model is developed after point cloud generation to approximate the original surface of the panel. This CAD model takes the form of a 3D mesh fit surface, which is created using the Mesh Fit tool in Design X. This fits a 3D surface to regions of the point cloud manually specified by the user. The 3D scan data used as reference for the surface fit is reduced to only include points corresponding to undamaged regions of the panel. This process is illustrated in Figure 3. The number of selected undamaged regions required to perform the analysis depends on the amount necessary to encompass the specified damage region beneath the surface fit.

Once the reference surface has been determined, the deviation between the point cloud data and surface fit is quantified, from which dent depth and contouring information may be extracted. The displacement between the 3D scan data and surface fit is obtained using the Deviation Analysis tool in Design X. This capability is a color map-based tool, which outputs the difference between a meshed object (usually based on 3D scan data) and a modeled solid or surface [13]. This software feature is primarily used to check feature accuracy during modeling; receiving real-time information regarding features (maintaining design intent) when making design decisions [13]. The described analysis is performed independent of reference frame or coordinate system because each deviation measurement is made normal to the surface fit. As a result, the panel can be oriented in any arbitrary direction when performing a scan.

The settings employed for this method depend on the level of detail required by the user. For the described analyses, specification of High Resolution and Fine Sampling for the deviation analysis were preferred, which are defined using the Accuracy Analyzer™ tool in Design X. High Resolution provides a color map of finer resolution, whereas Fine Sampling calculates deviation more accurately [13].

A critical factor during method setup is the definition of tolerance for the analysis. This is important because it represents the limit at which a deviation may be considered a dent impression. The goal is to choose a tolerance value, referred to as dent tolerance for the described analysis, which yields deviation results similar to the damage topography of the panel observable by eye, while not allowing natural surface deviations of the panel to skew individual dent impressions. In terms of honeycomb composite panels, the nature of the core damage beneath the face sheet must also be considered. This is true because the identification of barely visible dents is often required, which may hide critical damage in the core. Performance of a dent tolerance study on the described aircraft panels yielded a dent tolerance value of 0.1 mm. This indicated that a dent with depth less than 0.1 mm would not be identified during analysis. This tolerance is illustrated via the color green in subsequent figures, which illustrate the results of the method and indicate areas where the measured deviation falls within the range {-0.1, 0.1} mm.

The process of executing the 3D scanning method is illustrated in Figure 4. Here, four undamaged regions were manually selected to evaluate a local damage region, which comprised a central dent with complex shaping surrounded by several smaller dent impressions.

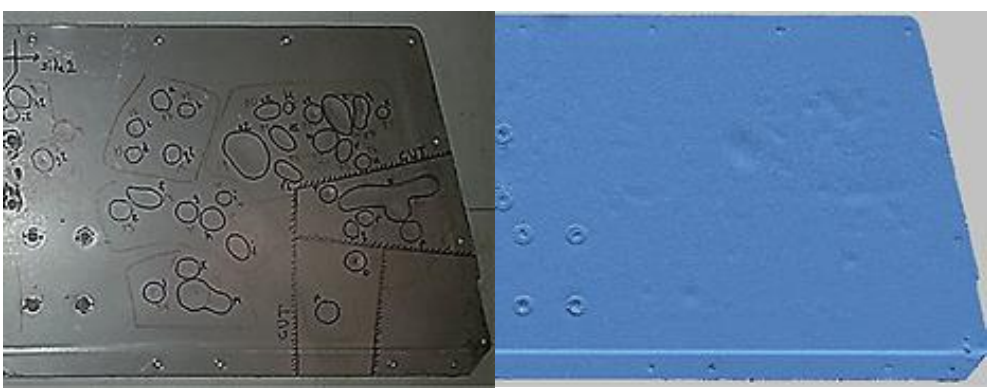

Figure 2. Retired aircraft panel surface (left) and 3D point cloud rendering (right)

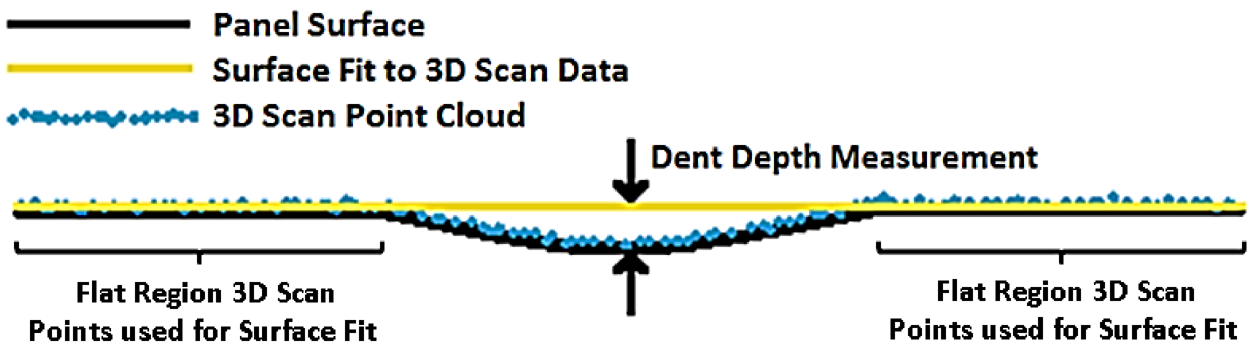

Figure 3. Diagram of 3D scanning method

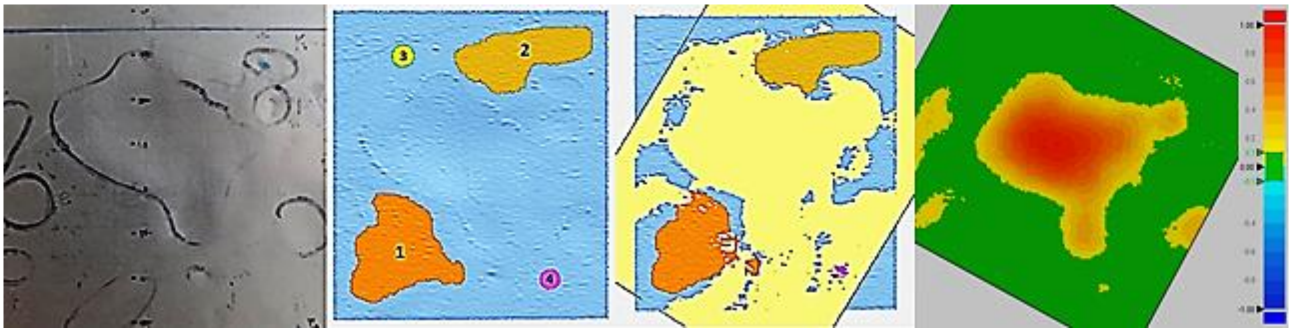

Figure 4. 3D scanning methodology; i) photo of local damage region; ii) scan data for damaged surface with four manually selected undamaged regions; iii) scan data with surface fit; iv) numerical results of deviation analysis showing contour data for damage area [0.1 mm tolerance]

2.2.1 Surface fit specifications

The 3D scanning method requires identification and selection of undamaged regions, or Region Groups, which surround dent impressions. For approximately flat panels, a region group study indicated that selection of these regions may be performed with some lenience in terms of user-specification. This study was performed on the damage region first presented in Figure 4, and revealed that a maximum dent depth measurement of 1.02 mm could be replicated across three unique analyses with only slight variations in dent contouring. These results are shown in Figure 5. This indicated that the shape or number of Region Groups is irrelevant as long as they surround a dent and are chosen within undamaged regions.

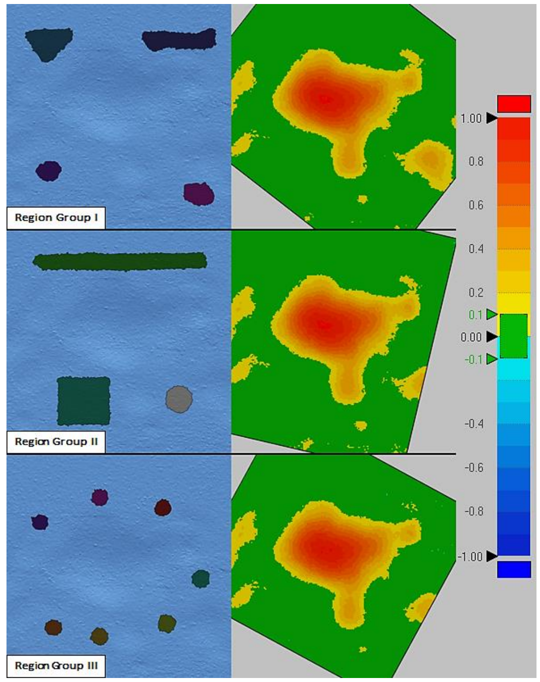

Figure 5. Region group study results; i) Region Group I; ii) Region Group II; iii) Region Group III [0.1 mm tolerance]

2.2.2 Damage depth analysis

The 3D scanning method may be extended to analyze broad surface regions such as entire aircraft panels, as shown in Figure 6 for the panel first presented in Figure 2. Dent depths may be found via manual probing in Design X or may be automatically output using Geomagic Control X software after importing point cloud and surface fit data.

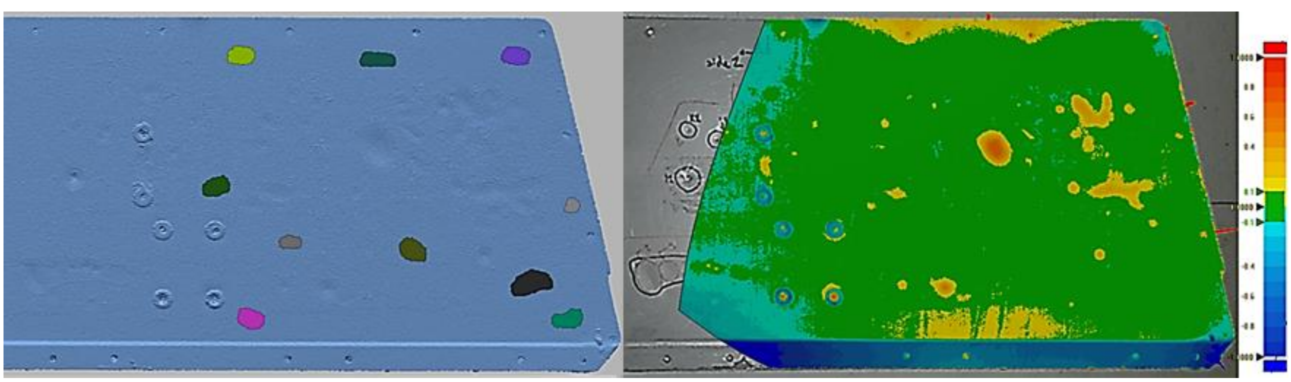

Figure 6. Point cloud data for dented panel surface with 10 manually selected undamaged regions (left); resultant deviation analysis transposed onto image of actual panel (right) [0.1 mm tolerance]

2.2.3 Damage area analysis

The color map-based results provided by Design X or Control X may be captured and analyzed using external programs such as Image J to measure parameters such as dent length (or Feret diameter) and dent area, among others. Feret diameter pertains to the maximum length that may be measured across a 2D shape, sometimes referred to as caliper diameter. The process of measuring dent length and area in this way is described below and illustrated in Figure 7:

1. Execute the deviation analysis with the color bar setting set to solid color. This yields a deviation analysis in which depth contouring is ignored and any deviation beyond the defined tolerance is presented as a single color.
2. Using a program such as ImageJ, convert the image to 8-bit greyscale. The image may also be processed via sharpening or despeckling, which reduce noise and may enhance the analysis of complicated damage regions.
3. Define the pixel/mm unit scale for the analysis using known dimensional information about the image provided in Design X or Control X.
4. Specify the parameters of interest for the analysis; for instance, area and Feret diameter
5. Use the Wand Tool to select individual dent shapes. Measurements taken for the selected shapes will correspond with the parameters defined for the analysis. These measurements are output directly in ImageJ, and may be saved in the form of a .csv file.

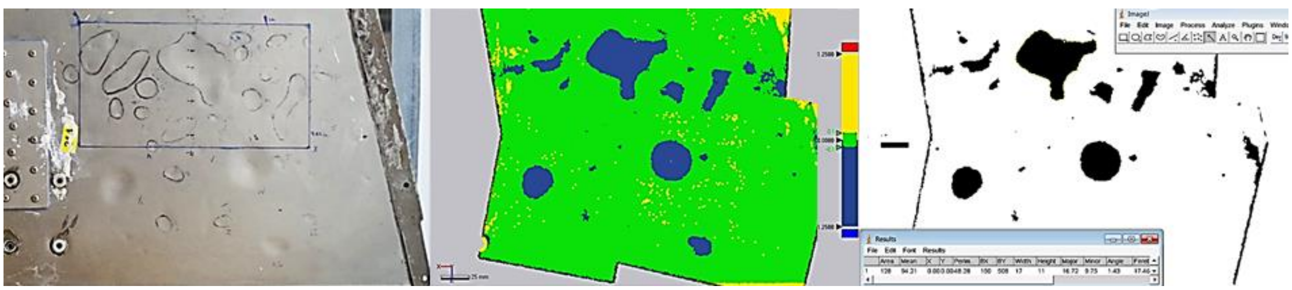

Figure 7. Methodology for damage area assessment; i) photo of damaged panel; ii) 3D scanning method results with solid color bar settings; iii) measurement of selected shapes in greyscale image

2.3 Results and validation

Results from the 3D scanning method were compared against measurements taken via Vernier caliper and coordinate measurement machine (CMM) for the primary dent shown in Figure 4. This was done using a 64-point sample of depth measurements taken over the dented surface. The positions of the measurements corresponded to an 8×8 grid drawn on the panel surface with 1 cm spacings, which was replicated in Design X as shown in Figure 8.

Comparison of the data revealed the 3D scanning method measurements to be within 0.0809 mm of those taken via Vernier caliper. The average absolute difference between the measurement sets was found to be 0.0260 mm, whereas the maximum dent depth measured between the methods was identical (1.01 mm). Dent shaping was also contrasted qualitatively in terms of dent perimeter, as shown in Figure 9. This comparison was made to evaluate dent contouring using the color map provided by the 3D scanning method and a 2D surface contour plot developed for the Vernier caliper data in Microsoft Excel.

Measurements were also taken within the 8×8 grid using the CMM capability of the FARO® ScanArm, which uses a touch probe to provide 3D spatial information about a subject. In this case, the 3D scanning measurements were found to be within 0.0761 mm of those taken via CMM. The average absolute difference between these two methods was 0.0301 mm. The maximum dent depths measured between the CMM and 3D scanning methods were 1.00 and 1.01 mm, respectively.

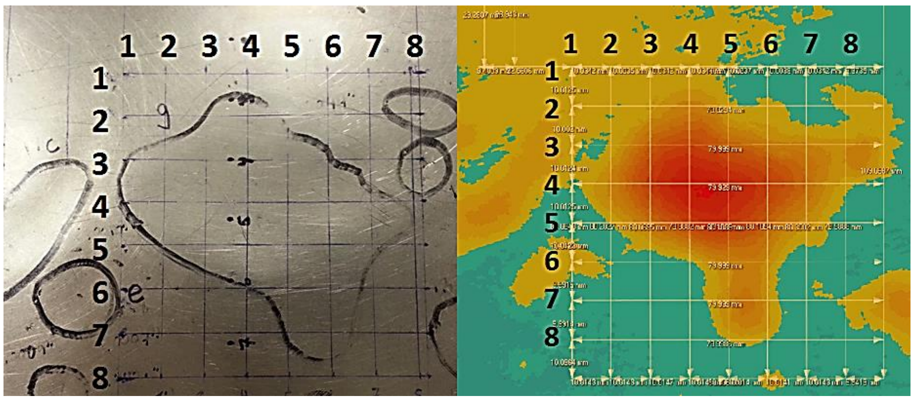

Figure 8. 8×8 grid replicated between actual panel and 3D scanning software for measurement validation

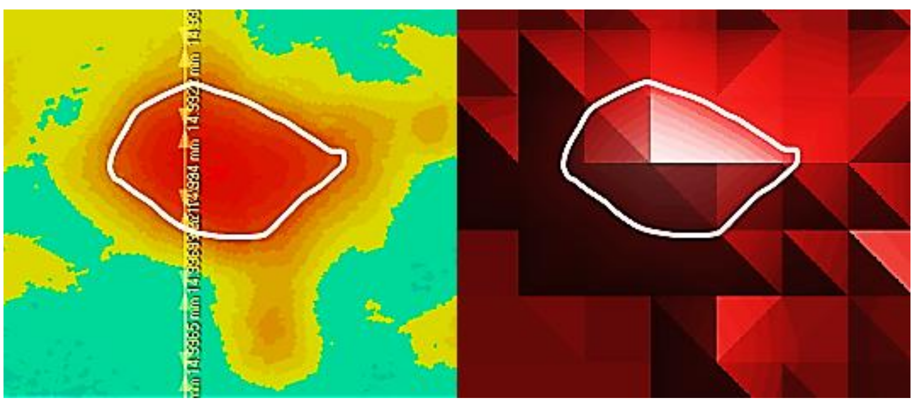

Figure 9. Dent contouring comparison; 3D scanning method (left) vs. Vernier caliper (Excel, right)

3 DISCUSSION

The 3D scanning method holds the potential for quicker and more reliable measurement of dent depths, lengths and areas than conventional techniques. It may also be more accurate in terms of identifying individual dent impressions and contouring. For instance, Figure 10 shows a damage region for the aircraft panel of Figure 8 in which the dent impressions identified via inspection personnel varied from those measured via the 3D scanning method. Here, dent contouring accuracy is important because it dictates the dent perimeter about which dent length is measured. This is critical because dent length is a parameter which defines panel lifetimes. As a result, greater accuracy in the measurement process may help avoid unnecessary panel replacement due to overconservative or inaccurate measurements.

There is also significant potential for in-field implementation of the method using portable, handheld 3D scanning tools. This is possible because the orientation of an inspection piece when using the 3D scanning method is arbitrary. There is also opportunity for automation of the undamaged region selection process, which would further reduce the susceptibility of the method to measurement variations based on human input. The same applies to the damage area analysis process, which currently uses a mixture of manual (dent identification) and automated (dent shape selection in ImageJ) features.

Comparisons between the dent depth data from the 3D scanning method and Vernier caliper indicated that the 3D scanning method agrees well with conventional manual methods while providing significantly higher data density in a shorter period of time. Notably, it was found that the process of performing the 3D scanning method on a damage region of 64 cm^2 area took approximately 5 minutes to complete, whereas performing manual measurements on the same region using a Vernier caliper took 20 minutes. Comparisons made between the 3D scanning method and CMM yielded similar results.

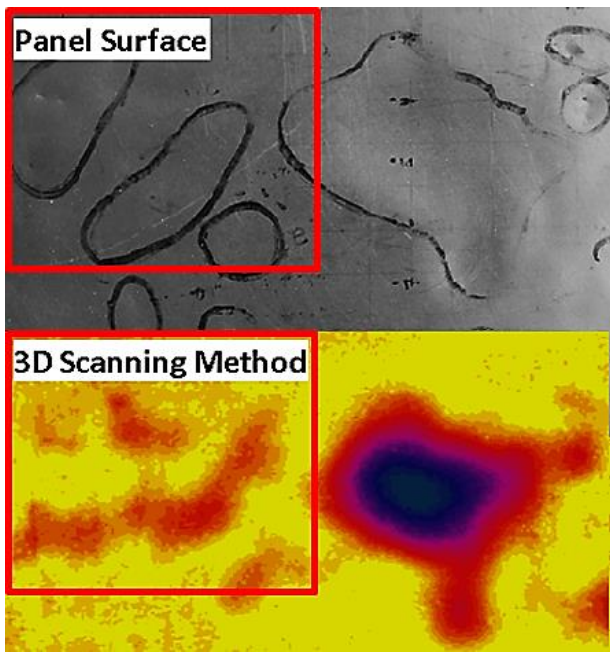

Figure 10. Comparison between dent shapes identified via inspection personnel (top) and the 3D scanning method (bottom)

4 CONCLUSIONS

3D scanning-based methods hold the potential to quickly and reliably measure surface damage parameters including dent depth, length and area. They also hold the potential to identify individual dent impressions within a cluster of dents, as well as reveal the true contouring of dent impressions. The described method was found to be less susceptible to operator inconsistencies as compared to conventional damage measurement techniques, which vary by inspection personnel. The 3D scanning method was found to be accurate within 0.1 mm compared to Vernier caliper- and CMM-based techniques for a 64-point sample of depth measurements taken on an aluminum honeycomb composite aircraft panel. Furthermore, the described method demonstrates potential for in-field implementation using portable 3D scanning systems. As a result, this technique may support the timely extraction of surface dent measurements with respect to on-site component analysis.

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